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A TECHNICAL AND ECONOMIC EVALUATION OF WOOD CONVERSION PROCESSES: VOLUME I, MAIN REPORT

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Preface

This is the final report under Energy, Mines and Resources Canada (EMR) contract no. 23283-8-6091 entitled " A Technical and Economic Evaluation of Wood Conversion Processes". The report signifies the completion of all tasks of the project. The project was composed of four parts:

I. A complete technology review report covering the bioconversion of wood to ethanol

II. A report defining the approach and evaluation techniques used in the study

III. An engineering analysis of the Iogen process and development of a base case process design and economic performance estimates for a 1000-tonne-per-day ethanol facility

IV. Construction of a process simulation model configured on the base case design, using Lotus 1-2-3 software as the modelling medium

The purpose of the project was to provide EMR with a technical and economic assessment of the Iogen wood-to-ethanol process; to develop a simulation model for the process that is usable by government and private sector managers interested in the technology; and to define evaluation criteria to support forecasting future process improvement and associated economic consequences.

The final report will be furnished as a public document and be available from the Efficiency and Alternative Energy Technology Branch of EMR. Copies of the Lotus 1-2-3 based process simulation model will also be available on diskette.

Table of Contents

Preface iii

Abstract ix

Résumé xi

1 Executive Summary 1

2 Introduction 8

3 Technology Overview 9
3.1 Acid Hydrolysis Processes 9
3.2 Enzymatic Hydrolysis of Cellulose 10
3.3 Enzymatic Hydrolysis Processes 10

4 Base Case Process Design 12
4.1 Block Flow Diagram 12
4.1.1 Process Flow Diagram 13
4.1.2 Capital Cost Estimates 14
4.1.3 Operating Costs 14
4.1.4 Major Equipment List 14
4.2 Definition of Key Parameters 15

5 Computer Model 17
5.1 Lotus 1-2-3 Spreadsheet Model 17
5.2 Menu Functions of the Model 19

6 Base Case Assumptions and Results 21
6.1 Technical Process Parameters 21
6.2 Design and Economic Parameters: Input and Output Assumptions 21
6.3 Base Case Production Summary 22

7 Sensitivity Analyses 26
7.1 Technical Process Parameters 26
7.1.1 Enzyme Loading 26
7.1.2 Enzyme Productivity 28
7.1.3 Enzyme Titer 29
7.1.4 Enzyme Yield 31
7.1.5 Solids Loading 32
7.1.6 Hydrolysis Time 32
7.1.7 Hydrolysis Yield 34
7.2 Design and Economic Parameters: Input and Output Assumptions 35
7.2.1 Plant Scale 35
7.2.2 Feedstock Cost 36
7.2.3 Lignin Price 38
7.2.4 Molasses Price 39

7.2.5 Electricity Price 40
7.2.6 Capital Costs 41
7.2.7 Capital Recovery Factor 42
7.3 Sensitivity Analysis: Summary 44

8 Monte Carlo Simulations 48
8.1 Standard Process Simulation 49
8.2 Iogen Base Case Simulation 51
8.3 Improved Case Simulation 53
8.4 Monte Carlo Simulation: Summary 55

9 Second-law Analysis 57
9.1 Standard Process 58
9.2 Iogen: Base Case Process 59
9.3 Iogen: Improved Case Process 60
9.4 Improved Case with Co-Products 61
9.5 Second-law analysis: Summary 62

10 Conclusions 64
10.1 Enzyme Production 64
10.1.1 Lactose 64
10.1.2 Cellulose 65
10.1.3 Glucose and Xylose 65
10.2 Co-Products 66
10.2.1 Lignin 66
10.2.2 Molasses 68
10.2.3 Electricity 69
10.3 Alternate Processing Schemes 69
10.3.1 Lignin Extraction 69
10.3.2 SSF versus SHF 70
10.3.3 Xylose to Ethanol 70
10.4 Potential Process Improvements 71

11 References 74

Appendix A. Process Description ..... A 1

2 Unit Operations ..... A 2
2.1 Section 100 Feedstock Handling ..... A 2
2.2 Section 200-1 Steam Explosion Pretreatment .... A 3
2.3 Section 200-2 Enzyme Production ..... A 4
2.4 Section 200-3 - Enzyme Hydrolysis System ..... A 6
2.5 Section 300 - Fermentation (Batch) ..... A 8
2.6 Section 400 - Ethanol Purification ..... A 9
2.7 Section 600 - Offsite Tankage ..... A 11
2.8 Section 700 - Waste Treatment ..... A 11
2.9 Section 800 - Utilities ..... A 14

Appendix B. Technology Review ..... B 1
1.1 Feedstock Characteristics ..... B 2

1.2 Acid Hydrolysis of Cellulose ..... B 3
1.3 Acid Hydrolysis Processes ..... B 4
1.4 Enzymatic Hydrolysis of Cellulose ..... B 7
1.5 Enzymatic Hydrolysis Processes ..... B 8

2 Engineering Feasibility Studies ..... B 12
2.1 Dilute Acid Hydrolysis ..... B 12
2.2 Enzymatic Hydrolysis Processes ..... B 14

3 Technology: Current Status ..... B 17

4 Selected References ..... B 23

Appendix C. Process Evaluation ..... C 1

2 Methodology: ..... C 2
2.1 Process Synthesis. ..... C 2
2.2 Model Development. ..... C 3
2.3 Sensitivity Analysis ..... C 4
2.4 Monte Carlo Simulation ..... C 6
2.5 Second-law Analysis. ..... C 8

3 Summary: ..... C 11

Appendix D. Lotus 1-2-3 Computer Simulation Model
Introduction ..... D 1

2 Process Description ..... D 2

3 Operation of the Model ..... D 14
3.1 Lotus 1-2-3 Spreadsheet Model ..... D 14
3.2 Range Names and Location ..... D 16
3.3 Operating in two modes ..... D 17

4 Summary ..... D 18

Appendix E. Attachment: Spreadsheet Print Out ..... E 19

Table of Figures

Figure 1. Enzyme Productivity versus Ethanol Price 3
Figure 1. Monte Carlo Simulation: Improved Case 4
Figure 3. Block Flow Diagram for Iogen Process 12
Figure 4. Enzyme Loading vs Ethanol Price 27
Figure 5. Enzyme Titer versus Ethanol Price 28
Figure 6. Enzyme Titer vs Ethanol Price 30
Figure 7. Enzyme Yield vs Ethanol Price 31
Figure 8. Solids Loading versus Ethanol Price 32
Figure 9. Hydrolysis Time versus Ethanol Price 33
Figure 10. Hydrolysis Yield vs Ethanol Price 34
Figure 11. Plant Scale vs Ethanol Price 36
Figure 12. Wood cost vs Ethanol Price 37
Figure 13. Lactose Cost vs Ethanol Price 38
Figure 14. Lignin Selling Price vs Ethanol Price 39
Figure 15. Molasses Selling Price vs Ethanol Price 40
Figure 16. Eletricity Credit vs Ethanol Price 41
Figure 17. Capital Cost vs Ethanol Price 42
Figure 18. Capital Recovery Factor vs Ethanol Price 43
Figure 19. Technical Process Variables 46
Figure 20. Design and Economic Variables 47
Figure 21. Monte Carlo Simulation: a Standard Design 50
Figure 22. Monte Carlo Simulation: Iogen Base Case 52
Figure 23. Monte Carlo Simulation: Iogen Improved Case .. 55
Figure 24. Combined Monte Carlo Simulation Results 56
Figure 25. Second Law analysis: Standard Process 59
Figure 24. Second Law Analysis: Iogen Base Case 60
figure 27. Second Law Analysis: Improved Case 61
Figure 28. Second Law Analysis: Improved Case + Co-Products 62
Figure 29. Lignin Value vs Co-Product Credit 68
Figure 1. Process Flow Diagram ..... A 2
Figure b1. Low Temperature Acid Hydrolysis ..... B 5
Figure b2. High Temperature Acid Hydrolysis ..... B 6
Figure b3. Enzyme Production versus Ethanol Price ..... B 19
Figure b4. Enzyme Loading versus Ethanol Price ..... B 20
Figure c1. Enzyme Loading versus Ethanol Price ..... C 5
Figure c2. Enzyme Productivity versus Ethanol Price ..... C 6
Figure c3. Monte Carlo Simulation ..... C 8
Figure c4. Second-law Analysis ..... C 9
Figure d1. Iogen Process Flowsheet with Streams Numbers . D 3

Table of Tables

Table 11. Potential Process Improvements 5
Table 1. Battery Limits Capital Summary 23
Table 2. Estimated Cost of Production 24
Table 3. Energy Consumption by Operating Units 25
Table 4. Technical Process Parameters 44
Table 5. Process Design Parameters 45
Table 6. Monte Carlo Simulation: Standard Process 49
Table 7. Monte Carlo Simulation: Base Case 52
Table 8. Monte Carlo Simulation: Improved Case 53
Table 9. Comparison of Total Lost Work 63
Table 10. Lignin Markets, Market Size, Co-product Credit 67
Table 11. Potential Process Improvements 72
Table D1. First Window of the Material Balance ..... D 5
Table D2. Equipment Costs ..... D 5
Table D3. Utilities ..... D 7
Table D4. Feedstock Input Section ..... D 7
Table D5. Pretreatment Section ..... D 9
Table D6. Enzyme Production Section ..... D 9
Table D7. Hydrolysis and Fermentation Section ..... D 11
Table D8. Economic Output Section ..... D 12
Table D9. Input and Output Section ..... D 13
Table D10. Lists Range Names and Cell Locations ..... D 16

Abstract

The primary purpose of this project was to provide Energy, Mines and Resources Canada (EMR) with a technical and economic assessment of the Iogen wood-to-ethanol bioconversion process. The evaluation technique involved developing a computer simulation model of the process using the Lotus 1-2-3 spreadsheet program. The simulation model was based on an engineering analysis of the process, complete with heat and material balances and a preliminary economic assessment.

The computer model was used to run sensitivity analyses for the process and to estimate the parameters with significant economic impact and promise for future improvement to the process economics. The most important parameters were then used in Monte Carlo simulations to estimate the potential for future improvements and to assess the commercial potential of the process. Finally, the process was subjected to a second-law analysis. The second-law analysis assesses the thermodynamic efficiency of the process in terms of lost work potential. Technical improvements to the process should show a reduction in lost work and therefore improvement in the efficiency of the process.

The Iogen process is a highly optimised process using state-of-the-art technology for pretreatment and enzyme production. The base case design would use 1000 tonnes per day of aspen wood and would produce about 91 million litres of ethanol per year. Assuming no value for co-products, the break-even selling price for ethanol would be between 45 and 70 cents per litre, depending on the financing method employed, i.e. the assumed capital recovery factor. If co-product credit is added for lignin and molasses, the required ethanol selling price would drop to between 30 and 50 cents per litre.

Forecasts for future technology improvements show that the economic feasibility remains heavily dependent on the value of the co-products; however, it is possible to construct scenarios where the ethanol price could be as low as 10 to 20 cents per litre, including co-product credits, and between 20 and 35 cents per litre without the co-product credits.

Potential improvements to the process include the following: reduced enzyme requirements; reduced enzyme production cost; xylose fermentation to ethanol; lower cost feedstock; and substitution of wood sugars for lactose for enzyme growth.

These low values for the required ethanol selling price could be achieved within the next five years if the rate of technology improvement continues at the pace experienced over the past five years, and assumes that C5 fermentation to ethanol is commercially ready in the same time period.

The basic methodology developed to evaluate the Iogen process is of general utility and applicable to any new or emerging technology. The author feels it would be valuable to apply this approach to other processes for energy production from renewable feedstocks, particularly the thermoconversion, liquefaction technologies.

Résumé

Le principal objectif de ce projet était de fournir à Énergie, Mines et Ressources Canada (EMR) une évaluation technique et économique du procédé de bioconversion de bois en éthanol développé par Iogen. La technique d'évaluation consistait notamment à mettre au point un modèle de simulation sur ordinateur du procédé au moyen du chiffrier électronique Lotus 1-2-3. Le modèle fut créé à partir d'une analyse technique complète du procédé notamment des bilans thermiques et massiques, ainsi que d'une évaluation économique préliminaire.

Le modèle fut utilisé pour soumettre le procédé à des analyses de sensibilité et estimer les paramètres ayant des répercussions économiques notables ainsi que les possibilités d'améliorer dans l'avenir l'aspect économique du procédé. Les paramètres les plus importants servirent ensuite dans des simulations de Monte Calro visant à estimer la possibilité d'apporter des améliorations au procédé dans l'avenir et à évaluer son intérêt commercial. Enfin, le procédé a fait l'objet d'une analyse fondée sur le deuxième principe de la thermodynamique du procédé en terme de possibilité de travail perdu. L'apport d'améliorations techniques au procédé devrait se traduire par une réduction du travail perdu, et de là, par une amélioration de l'efficacité du procédé.

Le procédé d'Iogen, qui a un rendement élevé, utilise une technologie de pointe aux étapes du traitement préalable et de la production d'enzyme. Dans le cas de base, l'utilisation de 1000 tonnes de tremble par jour permettrait de produire environ 91 millions de litres d'éthanol par année. Lorsqu'on suppose que les co-produits n'ont aucune valeur et qu'on utilise le facteur de recouvrement du capital présumé comme méthode de financement, le prix de vente au seuil de rentabilité se situe entre 45 et 70 cents le litre dans le cas de l'éthanol. Lorsqu'on attribue une valeur monétaire à la lignine et à la mélasse en tant que co-produits, le prix auquel l'on peut vendre l'éthanol diminue, variant de 30 à 50 cents le litre.

Selon des prévisions touchant les améliorations de cette technologie dans l'avenir, la rentabilité du procédé demeure très dépendante de la valeur des co-produits; il est toutefois possible de créer des scénarios dans lesquels le prix de l'éthanol pourrait être de 10 à 20 cents le litre lorsque les co-produits ont une valeur monétaire, et de 20 à 35 cents le litre sans co-produits à valeur monétaire.

Parmi les améliorations qui pourraient être apportées au procédé, signalons des besoins en enzyme réduits; un coût de production d'enyzme diminué; la transformation de xylose en éthanol par fermentation; une charge d'alimentation de coût moins élevé; et le remplacement du lactose par des sucres de bois aux fins de la

production d'enzyme.

L'éthanol pourra peut-être se vendre à ces prix peu éleves au cours des cinq prochaines années si l'amélioration technologique se poursuit au rhythme des cinq dernières années et si le procédé de production d'éthanol par fermentation de C5 devient, entretemps, commercialisable.

La méthode de base mise au point pour évaluer le procédé d'Iogen est utilisable à des fins générales et applicable à n'importe quelle technologie nouvelle ou en voie d'élaboration. L'auteur estime qu'il serait intéressant d'appliquer cette façon de faire à d'autres procédés aux fins de la production d'énergie à partir de charges d'alimentation renouvelables, particulièrement les technologies de la conversion thermique et de la liquéfaction.

1 Executive Summary

The principal objective of this report was to conduct a technical and economic evaluation of the Iogen enzymatic hydrolysis process for converting wood to ethanol. The evaluation includes an assessment of the current status of the technology and projections for future improvement.

The report consists of five parts:

- The main body of the report with the analysis and conclusions.
- Appendix A - the engineering analysis for the base case design.
- Appendix B - a wood-to-ethanol technology review.
- Appendix C - A review of the process evaluation techniques used to complete this report.
- Appendix D - A complete description of the Lotus 1-2-3 model developed to simulate the Iogen process.

Attached to the end of the report in Appendix E is a printout of the entire Lotus 1-2-3 computer model.

Each of the five individual parts of the report can be a free-standing report, however, the group of reports work together to tell a more complete story. The technology review provides a general context to understand the process; the engineering section contains the detailed description of operation of the basic plant design; and the process evaluation section describes the particular techniques used in the analysis and the rationale for their selection. The model description section describes how the model was constructed using the engineering data from the engineering section. Finally, the main body of the report uses all the above data and information to generate the analysis and projections regarding the present and future economic potential for the process.

The project was completed as follows: first the technology review paper was completed and submitted to EMR; then the section on technology evaluation techniques was completed. The base case process engineering was done along with complete heat and material

balances, capital cost estimates based on the ICARUS computer-assisted costing program and an estimate for the base case economic performance.

The engineering design was the basis for construction of the Lotus 1-2-3 computer process simulation model. The computer model was used to run sensitivity analyses and Monte Carlo simulation. The results of these analyses provided the data for many of the conclusions and concerns discussed in the main body of the report.

The Iogen process is a state-of-the-art enzymatic hydrolysis for converting wood to ethanol. The principal strengths of the process, that set it apart for competing processes, are the steam-explosion pretreatment and high rate for enzyme production (and thus low cost for enzyme).

Wood has three principal components: cellulose, hemicellulose and lignin. The hydrolysis process converts the cellulose to glucose, which is subsequently fermented to ethanol.

The structure of native wood is very complex and difficult to penetrate with chemical or microbiological agents. In the native wood, the cellulose is surrounded by hemicellulose and lignin in a matrix that is nearly impossible for enzymes to penetrate. Steam-explosion treatment opens the matrix and greatly increases the cellulolytic surface area available to enzymic attack. This pretreatment is the most cost-effective currently under development.

Lactose sugar from cheese whey is used as the carbon source for growing the cellulase enzyme complex in the Iogen process. The current productivity is in excess of 400 international units per liter per hour (I.U.). The estimated ethanol selling price is about 50 cents per liter. The importance of enzyme productivity is seen in the Figure 1.

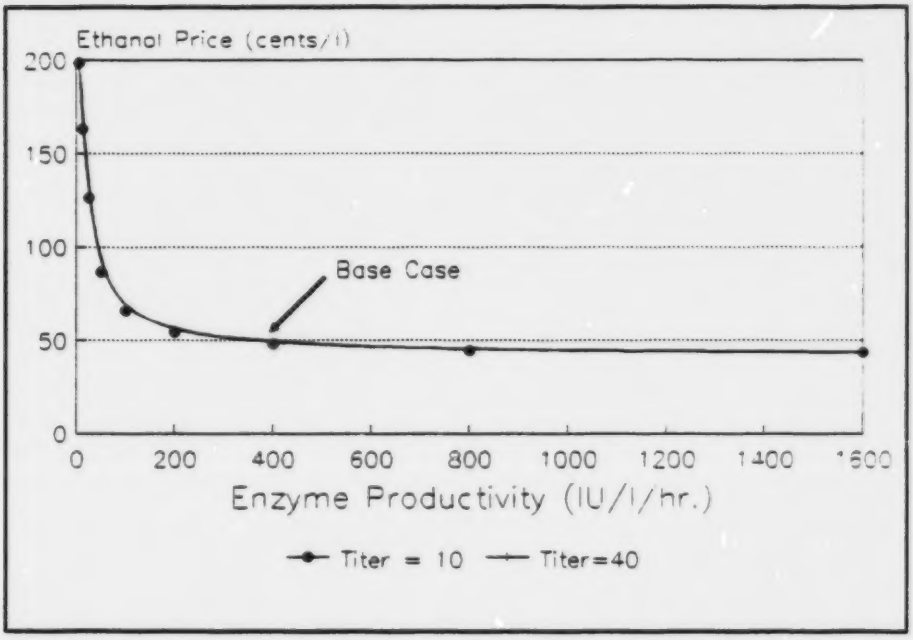

Figure 1. Enzyme Productivity versus Ethanol Price

If cellulose is used as the carbon source for enzyme production, the highest rate of productivity achieved to date is in the range of 50 to 100 I.U. The consequence of this lower productivity is an increase in the ethanol selling price to $1 to $1.50 per liter. This curve illustrates the importance of productivity to the economics of the process; it is important to note that additional increases in productivity can be expected through further research, and also that alternate carbon sources must be developed in order to fully exploit the commercial potential of this technology.

A Monte Carlo simulation was run to approximate an improved case for the process. Two simulations were run, with and without lignin co-product credit. Figure 2 shows the results of this simulation.

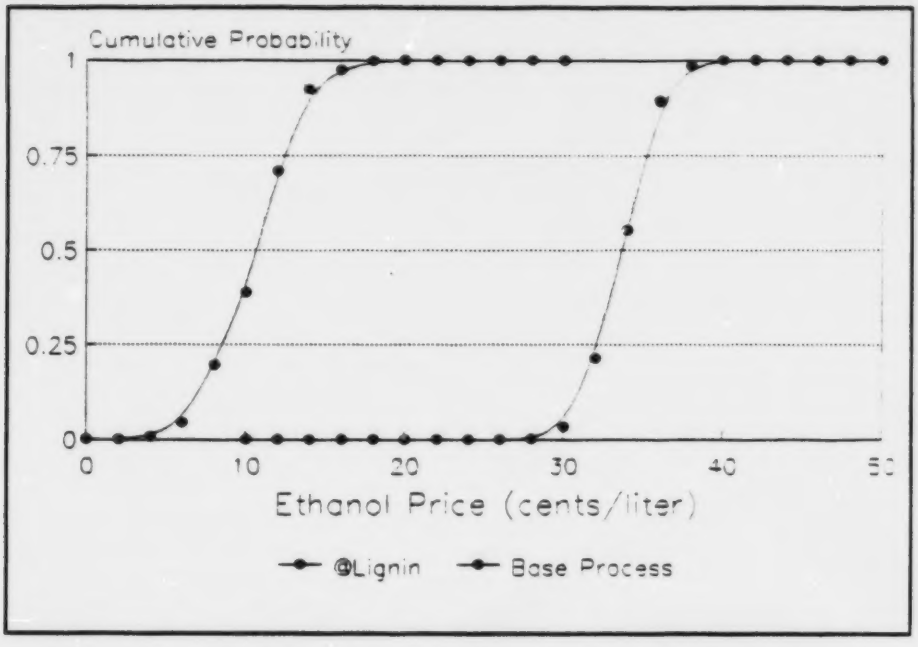

Figure 2. Monte Carlo Simulation: Improved Case

The inputs to the simulation were selected for their potential impact on the process economics and a reasonable expectation for attainability through research and engineering improvements to the process. The resultant simulation indicated that the ethanol price would be reduced to about 34 cents per liter for the base process and to about 12 cents per liter if co-product credit for lignin is included at 22 cents per kilogram.

Conclusions:

The Iogen process is a state-of-the-art process for the enzymatic conversion of the cellulosic fraction of woody feedstocks to ethanol, that features co-production of chemicals and animal feed from the lignin and xylose fractions. The co-products add significant revenues to the plant and, therefore, enhance the economic potential of the process. In fact, without these co-product credits it is doubtful if this, or any wood-to-ethanol process, could compete in the commercial environment.

Table 11 (below), from section 10.4, shows the economic impact of process improvements in five key areas. The net effect if all five goals are accomplished will be to reduce the require ethanol selling price by 18.89 cents per liter to 29.15 cents per liter from the

base case ethanol price of 48.04 cents per liter, without co-product credits. If co-product credits are added for lignin at 22 cents per kilogram and molasses at 12.1 cents per kilogram the require ethanol selling price is reduced to 11.10 cents per liter. If the C5 sugars are converted to ethanol instead of molasses the required selling price for ethanol is 14.25 cents per liter.

These results point out the areas of technological improvement that produce the greatest change to the economics posture of the Iogen process. Each of these process targets is achievable with an additional 2 to 3 years of research and engineering development.

Table 11. Potential Process Improvements

Process Step	Base Case	Improvement	Delta Ethanol Price
Enzyme productivity	400	1600	-5.61
Enzyme loading	25	10	-8.27
Glucose yield	85%	100%	-7.47
Solids loading	15%	20%	-2.83
Enzyme yield	250	400	-2.39

	Ethanol Price cents/liter
The net impact of summing these changes would result in an ethanol price of:	29.15
With co-product lignin at 22 cents per kg and molasses at 12.1 cents per kg, the ethanol price	18.14 11.10

With xylose fermentation the ethanol price is	21.00
and with lignin co-product credit at 22 cents per kg	14.25

The ultimate potential of the Iogen process will be determined by the co-product value obtained for the lignin and molasses, and with further improvement in fermentation of xylose sugar to ethanol. The economic impact of this additional alcohol, from xylose, could reduce the required ethanol selling price by 15.25 cents per liter

from 48.04 to 32.79 cents per liter for the Iogen base case; in the improved case described in Table 11 this additional ethanol will drive the ethanol price down to about 21 cents per liter. With the lignin credit at 22 cents per kg, the price would be about 14.25 cents per liter.

This is not as low as the improved case with xylose being sold as molasses, where the required ethanol selling price with lignin and molasses is 11.10 cents per liter. The principal reason for this effect is that the additional ethanol increases the amount of product by 40 percent and thus reduces the impact of co-product lignin. Also the additional capital costs associated with fermenting the xylose increases the net selling price of ethanol. As more research and engineering is completed on xylose fermentation to ethanol we can expect capital costs to be reduced and the ethanol price to be reduce by another 3 to 5 cents per liter.

If tree farming and genetic modification of tree stock succeeds in producing a feedstock that sells for $20 per tonne, then an additional reduction of 5 to 7 cents per liter in the required ethanol selling price would be obtained for these improved cases.

Recommended Areas for Process Improvement:

The three modifications to the Iogen process suggested below are offered as potential methods to improve an already highly optimized process. These are outside the natural evolution of process improvements that are ongoing at Iogen.

1. SSF versus SHF. End-product inhibition causes the enzymatic hydrolysis process to slow down after the accumulation of sugars in the hydrolysis reactor. The simultaneous saccharification and fermentation (SSF) processing approach removes sugar from solution as it is made, thus avoiding the problem of sugar accumulation. This reduced sugar accumulation also reduces the enzyme loading requirements for the process to the range of 10 I.U. per gram of cellulose. This translates to a reduction in the ethanol selling price from the base case value of 52 cents per liter to about 40 cents per liter.

2. Xylose to Ethanol. Conversion of the xylose (C5) sugars to ethanol would benefit the economics of the process by reducing the ethanol price from the base case value of 48.04 cents per liter to about 33 cents per liter. At present, the process to effect this conversion is a research issue, however, significant progress has been made to this end over the past two years. It is expected that

a viable system for xylose fermentation will be available in the next two years and this process stage should be integrated with the Iogen process design.

3. Extracting the lignin prior to hydrolysis has beneficial effects on the process economics. Removal of lignin reduces the size and capital cost of some of the down stream equipment. Lignin removed via alcohol or base is of higher quality than fermentation lignin typical of the product from the Iogen process. A "Higher quality" lignin means lignin that is free of major contaminants, such as, unhydrolyzed carbohydrates.

2 Introduction

Over the past 10 years, biological conversion of wood to ethanol has grown from a laboratory curiosity to a technology nearly ready for commercial development. Significant breakthroughs in pre-treatment of lignocellulosic feedstocks and development of superior microorganisms for producing cellulase enzymes have provided the principal thrust for propelling the technology toward commercial reality. Organisms that ferment xylose sugars to ethanol show great promise for adding to the commercial potential of these processes, as well as using the lignin fraction of the feedstock to produce fuels and chemicals.

Advances have been made in bioprocessing techniques that offer additional improvements to the economic performance of these systems. As yet, there are no commercial-scale facilities on stream to demonstrate the economic feasibility of these processes. The lack of a commercial facility is, therefore, a principal barrier to commercial exploitation of the technology, because the private sector is reluctant to assume the risk associated with building commercial-scale plants based on unproven technology.

A number of engineering and modeling studies have been completed for various conversion processes; however, a high degree of uncertainty remains regarding the economic promise of these processes. Part of the uncertainty lies in predicting the price of energy in the future, along with determining the crossover point for production costs for ethanol and petroleum-based fuels. Scale-up factors for moving bench-scale and research technology to pilot scale are highly uncertain. Finally, the current level of the technology will not produce ethanol at a price that is competitive with petroleum-based fuels, and the uncertainty of achieving targeted research goals limits commercial adaptation.

The purpose of this study is to evaluate the current status of the Iogen process for conversion of wood to ethanol, in terms of the technical and economic readiness of the process for commercial development. The study will focus on the technology through application of modern chemical engineering review, computer modeling and simulation, sensitivity analyses and Monte Carlo simulation, and Second law (of thermodynamics) analysis. The result of this study shall be an up-to-date analysis of the current status of the technology and an accurate prediction of future potential for improving the technical and economic performance of the process.

3 Technology Overview

The biological processing of woody feedstocks is a complicated undertaking that is controlled by the nature of the feedstock and the hydrolytic-attacking agent. This section includes a general discussion of acid and enzymatic hydrolysis of cellulose. Hydrolysis of cellulose refers to the addition of a water molecule to the cellulose polymer bond, causing the bond to sever and yield a glucose (sugar) molecule. Fermentation yeast can convert glucose to ethanol and not the polymer and polymer fractions of cellulose. Cellulose is converted to ethanol in two discrete steps: the cellulose is hydrolyzed to glucose, which is then fermented to ethanol. Fermentation technology is well developed; therefore, most of the recent research activity has centered on developing an economical method for optimizing the hydrolysis step.

Cellulose may be hydrolyzed to glucose enzymatically or chemically (with acid). Acid hydrolysis processes are hampered in that they require extreme conditions of high temperature and low pH. Such conditions make it necessary to employ expensive corrosion-resistant equipment. Conversion efficiency is limited due to glucose degradation in dilute acid systems. The substantial technical constraint requiring near total acid recycle limits the economic feasibility of concentrated acid systems.

On the other hand, enzymatic hydrolysis systems suffer from none of these difficulties. Enzymatic processes are performed at much less severe reaction conditions and have potential, due to the high specificity of enzymatic reactions, for total conversion of cellulose to glucose. However, enzymatic processes have been hindered by the high cost of enzyme production, the limited accessibility of the substrate to the enzyme, and slow reaction rates.

3.1 Acid Hydrolysis Processes

There are numerous processes and methods for using acid to hydrolyze lignocellulosic feedstocks. For this review, these various approaches will be separated into two broad types of processes: dilute acid processes and concentrated acid processes. Acid hydrolysis processes have been used for over 50 years -- some processes in Germany and Russia have been operated on a commercial scale. The Russian processes are used to produce single cell protein for use in animal feeds and not for ethanol production.

The Tennessee Valley Authority (TVA) has developed both concentrated and dilute acid hydrolysis pilot scale processes at their facilities at Muscle Shoals, Alabama. Both processes produce ethanol from woody feedstocks and while both processes are technical successes, neither process has shown any economic promise to date. These projects will probably be shut down during the current fiscal year due to this lack of economic promise.

3.2 Enzymatic Hydrolysis of Cellulose

Enzymatic hydrolysis of cellulose to glucose is performed by a class of enzymes called cellulases. Cellulase enzymes are composed of a complex group of enzymes, each of which plays a particular catalytic role in the depolymerization of cellulose to glucose monomer units.

Sources of cellulase enzymes include anaerobic protozoa, aerobic fungi, and aerobic and anaerobic bacteria. The most extensively studied cellulase enzymes have been produced from aerobic, mesophilic fungi, and of these, most researchers have focused on strains of Trichoderma reesei. These organisms are of interest because they secrete all the enzyme components necessary to hydrolyze cellulose; the cellulase produced is resistant to chemical inhibitors and is stable at temperatures of 50°C for up to 48 hours.

The cellulase complex consists of as many as 11 different enzymes. However, the activity consists of three main types of enzymes: Beta-1,4-glucan glucanohydrolase, an endo-enzyme; Beta-1,4-glucan cellobiohydrolase, an exo-enzyme; and Beta-glucosidase.

The action of this group of enzymes is very complex, where the exo- and endo-enzymes are thought to act together on the surface of the cellulose, while Beta-glucosidase acts on the soluble fractions split off by the surface enzymes. End-product inhibition limits reaction rates and extent. Glucose inhibits Beta-glucosidase, and cellobiose has been shown to inhibit the cellobiohydrolase enzyme. As the concentration of these sugars increases in the reaction media, the activity of the enzymes is reduced and can be totally stopped. A great deal of the research effort in enzymatic process technology is directed toward understanding and controlling these effects.

3.3 Enzymatic Hydrolysis Processes

Many different flowsheets have been proposed for enzymatic cellulose-to-ethanol processes, and all fall into one of three categories: (a) separate hydrolysis, fermentation and enzyme

production steps (SHF); (b) simultaneous saccharification and fermentation (SSF), which combines the hydrolysis and fermentation reactions in one step; and (c) direct microbial conversion (DMC), which combines all three steps of enzyme production, hydrolysis and fermentation.

A detailed review of the different technology approaches is presented in Appendix C.

4 Base Case Process Design

The base case process design is the key element in determining the technical and economic feasibility of any new technology. Therefore, the evaluation of the Iogen enzymatic hydrolysis wood-to-ethanol process was started by constructing a base case process design. The design was accomplished by completing the following steps:

1. A block flow diagram was prepared, followed by the assembly of a rough process flow diagram; the capital and operating costs were estimated; and the major equipment listed.

2. When the above data were compiled, the base case ethanol production costs were estimated.

4.1 Block Flow Diagram

The block flow diagram for the Iogen process is shown in Figure 3 and illustrates the general material flows and process options in the process.

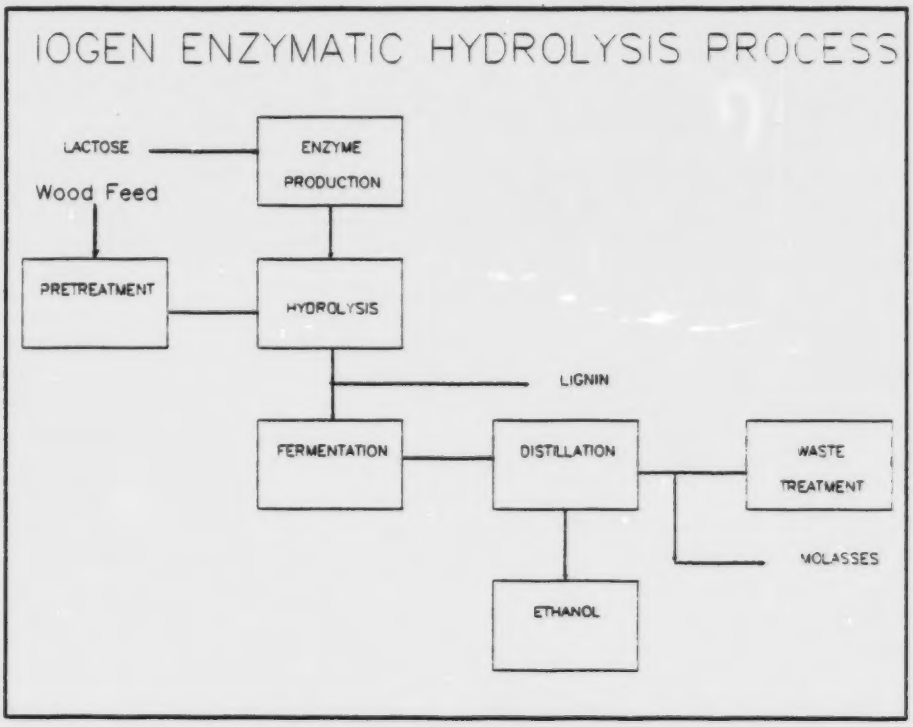

Figure 3. Block Flow Diagram of Iogen Process

The process has two input streams: wood into the steam explosion pretreatment section and lactose into the enzyme production section. The outputs from the process include ethanol as the major product and optional by-products from lignin and molasses. In the base case, the lignin and molasses streams are dried and used as boiler fuel to provide process steam and electricity for the plant. The unique characteristics of this process are found in the pretreatment and enzyme production sections. Conventional technology is used for the hydrolysis, fermentation, distillation and waste treatment sections of the plant.

Steam explosion is used as the pretreatment and produces a substrate that is easily hydrolyzed. The steam treatment causes the release of lignin from the lignocellulosic matrix and allows easy access for the enzyme to attack the cellulose fibers. The process produces a higher surface area that enhances the rate of hydrolysis compared to alternate methods for pretreatment. The enzyme production section uses lactose sugars from cheese whey as the substrate for enzyme growth. Using a liquid substrate increases the rate of enzyme production and reduces the enzyme production costs. The Iogen process has an enzyme growth rate that is 5 to 10 times higher than conventional technology which uses cellulose as the carbon source for enzyme production.

4.1.1 Process Flow Diagram

In this step, the process was fully defined. The process stream composition and sizes, into and out of the individual unit operations, were determined and the material balances calculated for each unit. The process flows were integrated, and then the total material balances for the process were calculated. The estimates developed for the material balances were a key element of the design process and provided the foundation for the remainder of the evaluation procedure.

This is the most critical section of the study, because the basic design data is collected during this stage and the validity of all subsequent analysis depends on the accuracy of this step. The importance of this section should not be minimized. Completion of this section involved close cooperation between Iogen staff members and the principal engineer of Entropy Associates. Two principals from Entropy Associates traveled to Ottawa to meet with staff members from Iogen, review the process and conduct an on-site visit of the Iogen facilities. The on-site meeting was followed by several telephone discussions and information exchange via mail and FAX transmissions.

The base case process design generated for this study is based on

the process information and data provided by the Iogen staff.

4.1.2 Capital Cost Estimates

After completing the material balances and defining the stream sizes for the process, the equipment sizes and materials of construction were estimated. Based on the estimated equipment sizes, the capital cost for the individual unit operations were estimated and the total plant cost estimated by summing the cost for the unit operations. The capital cost estimates were obtained by generating updated ICARUS[1] values from an unpublished 1986 Solar Energy Research Institute (SERI) report in which a similar process was evaluated, and by reference to the A.D. Little data in its 1985 report (A.D. Little, 1985) on the Iogen process.

[1]Note: The ICARUS program is a computer-aided method for estimating capital and operating cost for new plants. The ICARUS COST systems are used for estimating and scheduling engineering, and construction costs for oil, petrochemical, chemical, and pharmaceutical process plants by most of the top U.S. engineering contractors. This system was the basis for estimating the capital and operating costs for six different ethanol process approaches in a 1986 SERI engineering review of ethanol from wood technology.

4.1.3 Operating Costs

The operating costs were determined by calculating the raw material requirements and costs, the utility requirements, and the manpower and maintenance costs. The raw material requirements were calculated from the material balances on the process. The utility requirements were established by completing a heat and electrical energy balance on the process. The manpower and maintenance values were estimated by updating the ICARUS computer-aided cost estimating model results from the unpublished 1986 SERI study (by J. Wright and A. Power).

4.1.4 Major Equipment List

The major equipment list, with purchase costs, was developed from the ICARUS output sheets and by scaling up the data from the A.D. Little report (June, 1985). The details for this data are documented in Appendix A.

4.2 Definition of Key Parameters

While developing the process flowsheet for the Iogen process and subsequent computer model, several process areas stood out as key elements to the successful economic performance of the process. Pretreatment, enzyme production and hydrolysis were the key areas. These areas are interdependent in that a more efficient hydrolysis occurs with higher enzyme loading. Improved pretreatment would produce a substrate requiring less enzyme loading to achieve a specific hydrolysis yield. All the variations of these interactions can come into play in an analysis of enzymatic hydrolysis processes.

The results obtained using the general method for measuring enzyme concentration is quite ambiguous, that is, the standard measure, the international filter paper unit (I.U.), is based on the DNS colorimetric assay. The DNS assay measures the concentration of reducing sugars in solution, and therefore counts xylose and other reducing sugars along with the glucose.

The assay is sensitive to the amount of beta-glucosidase in the enzyme complex. DNS does not react with cellobiose and other cellodextrines, therefore enzyme solutions that are deficient in beta-glucosidase will give results that are too low. An accurate cellulase assay should measure the total glucose released in the hydrolysis of cellulose and not the xylose and other non-glucose sugars from the hemicellulose fraction of the feedstock.

[Note: The reason for this short discussion on enzyme assays is to issue a warning: Do not take any value printed for enzyme productivity and enzyme titer as absolute. However, understand that these values are subject to potential variations. The variations have to do with the testing procedures and are not associated with research and engineering effort at Iogen. This is a shared responsibility within the biotechnology community.]

The parameters discussed below assume that a fixed pretreatment system is used, meaning that interactions sensitive to changes in substrate are omitted.

The key parameters are:

- Enzyme loading refers to the amount of cellulase enzyme required per gram of cellulose in the hydrolysis reactor, expressed in I.U. of enzyme per gram of cellulose.

- Enzyme productivity is the rate of enzyme production and is expressed in terms of I.U. per liter per hour, e.g., the growth rate of the enzyme per unit volume of fermenter per hour.

- Enzyme titer is the concentration of enzyme in the fermentation broth at the end of the growth process. The titer is expressed in I.U. per milliliter of solution.

- Enzyme yield is the number of I.U. of enzyme produced per gram of carbon substrate, in this process the carbon source in lactose.

- Hydrolysis yield is the percentage of the potential glucose that is liberated during hydrolysis.

These process-related parameters are the principal economic drivers for the Iogen process. The co-products provide additional improvement to the economic performance of the process.

5 Computer Model

This section contains a generalized description of the Lotus 1-2-3 computer simulation model of the Iogen process. The application of the model to generate sensitivity analyses, Monte Carlo simulations and second-law analyses is illustrated and the results discussed in Sections 7, 8 and 9, respectively.

5.1 Lotus 1-2-3 Spreadsheet Model

The base case design described in Section 6 and Appendix A was used as the basis for constructing a computer model of the Iogen process. The model was developed on the Lotus 1-2-3 spreadsheet software and uses the same general format as the generic model described in detail in Appendix D. The Iogen SHF model has several features that were not part of the generic model, namely:

- The model is feedstock driven, i.e., the amount of wood, in tonnes per day, entering the plant is one of the input variables.
- A second version of the model is production driven, i.e., the amount of ethanol output of the plant determines the plant scale and is one of the variables in the process.
- The operator can choose to have lignin and molasses as by-products of the ethanol production or have these streams sent to the boiler to furnish process heat and electricity.
- The model is also connected to a Lotus 1-2-3 based economic analysis program, labelled as RETA 123. By selecting the (\R) macro it is possible to save the economic output in a RETA-compatible file.
- The model is menu driven such that by calling alt-M (\M) the menu macro, the operator can easily move to any section of the model. The menu facilitates selecting specific input and output sections for review and analysis.
- The cells containing input variables are highlighted for easy identification.

The variables available as inputs to the model include:

- Tonnes of wood per day
- Feedstock composition
- Enzyme titer
- Enzyme productivity
- Enzyme yield
- Glucose yield
- Enzyme loading
- Solids loading in the hydrolysis reactor
- Hydrolysis time
- The cost of cheese whey
- The cost of wood
- The value of molasses
- The value of lignin
- The value of electricity
- Options to: co-produce lignin as a chemical, and molasses or ethanol from C5 sugars
- Additional Options: Additional wood or natural gas to supply the energy requirement of the plant

The outputs from the model include:

- Ethanol production volume in liters per year
- Required ethanol selling price in cents per liter
- Plant capital and operating costs
- Amount and value of co-product credits (if applicable)
- Output file for the RETA 123 economic model

The final version of the Lotus 1-2-3 model of the Iogen process is on a diskette and is included with this report. The model includes modifications to enable the user to select wood or natural gas as alternate energy sources when xylose and lignin are used for co-products, and to select ethanol from xylose rather than molasses production. The final version of the model was used to generate all the analyses included in this report, including the sensitivity analyses, the Monte Carlo simulations and the second-law analyses.

5.2 Menu Functions of the Model

Three macros are provided to improve the ease of operating the Iogen model: Alt-Z, the recalculation macro; Alt-M, the menu macro; and Alt-G, the graphics macro.

The Alt-Z macro should be use to recalculate the output-driven model any time the amount of feedstock input changes. This requirement is necessary because the basis of the model operation is an accurate calculation of the material balance, and this occurs only when the Alt-Z macro is invoked. Most of the other mathematical interactions are independent of the amount of substrate and therefore do not require recalculation using Alt-Z to assure accurate updating.

For example, if the enzyme loading is changed from 25 I.U. per gram of cellulose to 40 I.U. per gram and no other changes were effected, the enzyme production section would increase in size to accommodate the increased amount of enzyme required. However, the amount of wood does not change and the basic material balance on wood would not change. This is a consequence of the independence between the wood stream and the enzyme production section of the process.

Most of the process parameters behave in a similar manner and only require a function key (F9) keyboard recalculation. If in doubt, the user should select the Alt-Z macro; it only requires a few additional seconds of processing time.

The menu macro Alt-M, calls up a top line menu similar to the menus normally called in by the Lotus program, only in this case the menu allows the user to move around the spreadsheet model to selected areas. The menu has seven labels: Input, Cap_Cost, EnzProd, Summary, Hydrolysis, RETA_File and Quit.

Selecting any of these labels will move the user to that section of the spreadsheet model.

- The **Input** section has three areas; a. The feedstock composition, b. The amount of feed input in tonnes per day, and c. The by-product decision area, i.e., whether to extract lignin and molasses as by-product streams.

- The **Cap_Cost** section contains the base case capital cost data and scale factors used to calculate the new capital cost when operating parameters that effect plant or equipment sizes are changed.

- The **EnzProd** section contains the input assumptions used to determine the enzyme productivity. The principal parameters are enzyme titer, soluble protein and fermentation time.

- **Summary** is the section containing the output from the model and summarizes the economic components that add up to the ethanol production costs. This is the first level area for evaluating the economic impact of parametric changes.

- The **Hydrolysis** section contains the input assumptions that control the rate of hydrolysis. The principal parameters are solids loading, enzyme loading, hydrolysis time, and hydrolysis yield. Each of these parameters has a significant impact on the economics of the process.

- **RETA_File** is the section where the outputs from the model are stored in the format of the RETA economic model. The output from the RETA_File can be save in a separate (user-named) file for input in to the RETA model by calling the Macro Alt-R.

- **Quit** is the last entry and should be used to exit the menu when no choice is selected.

A detailed review and description of the model is included in appendix D at the end of the report.

The alt-G graphics macro is used to review the graphics data stored with the model in the form of named graphs. To invoke the macro, push alt-G and a menu will appear at the top of the screen. The first item on the menu is VIEW, which asks if the operator wishes to view the named graphs. Pushing return (or V) will bring up a list of named graphs, and by using the cursor keys, the operator can select the graph he wishes to display. The graphs on the diskette are the sensitivity analyses and Monte Carlo simulation results.

6 Base Case Assumptions and Results

The base case design was developed by using the operating parameters currently being run at the Iogen one-tonne-per-day pilot facility; assuming these data could be scaled to a 1000 tonnes per day. We found no equipment, engineering, nor fundamental technical barriers that would limit the development of the large scale plant. The design parameters are defined in sections 6.1 and 6.2 called the technical process parameters and design and economic parametrs, respectively. Section 6.3 contains the base case productions costs summary.

6.1 Technical Process Parameters

The technical process parameters are the physical and chemical characteristics whose changes will effect changes to the system performance and thereby modify the economic performance of the system. The base case value for each of these parameters is listed below:

- Enzyme loading - 25 I.U. per gram of cellulose
- Enzyme productivity - 400 I.U. per liter per hour
- Enzyme titer - 40 I.U. per milliliter of broth
- Enzyme yield - 250 I.U. per gram of lactose
- Solids loading - 15 weight percent
- Hydrolysis time - 72 hours
- Hydrolysis yield - 85 percent

6.2 Design and Economic Parameters: Input and Output Assumptions

The design and economic parameters form a group of input and output controls for the process. These parameters set the scale of the process, the feedstock costs, and the value of the co-products. The co-products will require modification of the plant operation from the base case design, whereas the rest of these parameters do not impact the base process operation.

- The plant scale - 1000 tonnes per day of aspen wood.
- The feedstock costs - 42 dollars per tonne for aspen wood, and 23 cents per kilogram for cheese whey.
- The lignin value - 22 cents per kilogram, although no lignin was removed from the process in the base case design.
- The molasses value - 121 dollars per tonne, although molasses was not a co-product in the base case.
- The value of electricity - set at 2.92 cent per kwh.
- The capital cost for the plant - $121.2 MM.
- Annual capital recovery factor - 12.9 percent was used for the base case design.

6.3 Base Case Production Summary

The following data are the summary results from the analysis of the base case process design. These results are expressed in Canadian dollars.

CAPITAL COST SUMMARY

Basis:	U.S. Midwest location, 3rd quarter 1988
Capacity:	91,240,000 liters per year
	approx. 1,000 tonnes of wood per day
Operation:	8,000 hour per year

Battery limits	$121.2 MM
Offsites	(included in ISBL)*
Total Fixed Inv.	$121.2 MM
Working Capital	$ 12.1 MM

Table 1. Battery Limits Capital Investment Summary

Unit Operation	Total Unit Cost
Feedstock Handling	$ 7,938,000
Pretreatment	11,527,000
Enzyme Production	29,372,000 (*)
Chilled Water	122,000
Air Compression	1,423,000
Hydrolysis Reactor	13,577,000
Fermentation	2,852,000
Ethanol Purification	4,243,000
Tankage/Storage	4,900,000
Waste Treatment	8,400,000
Utilities	36,960,000
Total Capital Cost	**$121,193,000**

*[Note: Includes $1,082,000 for whey permeate receiving/storage/blending/ pasteurizing/feed system, adapted from the A.D.Little study (June, 1985). *ISBL means inside battery limits costs]

PRODUCTION COST SUMMARY

TABLE 2. Estimated Cost of Production Ethanol via Iogen Enzymatic Hydrolysis Process

Raw Materials	Unit/l	Price (C/Unit)	Annual Cost(M$)	Cent/l Product
Wood, Kg	3.65	4.20	14,000	15.34
Lactose, Kg	0.17	23.0	3,496	3.83
Corn Steep Liq., Kg	1.45	0.62	820	0.90
Other Chemicals, Kg	1.44	1.14	1,503	1.65
Total Materials Costs				21.72
Utilities				
Cooling Water, M Gal	.007	5.16	32	0.03
Steam and Electricity*				
Operating Costs and Expenses				
Operators			1,062	
Managers			260	
Direct overhead			632	
Maintenance			3,844	
General overhead			3,174	
Taxes/insurance			1,772	
Totals			10,744	11.78
By-Product credits			0	0
Excess electricity, Mwhr			(2,379)	(2.63)
Capital charges, 8%/yr			15,635	17.14
TOTAL COST OF PRODUCTION			43,832	48.04

* [Note: The plant as configured produces all its internal steam and power requirements by co-generation in a steam boiler/turbo-generator system, which exports excess electric power. Table 3 shows the summary of the steam and power usages for the process broken down by operating unit.]

Table 3. Energy Consumption by Operating Unit

Unit Operation	Electric Power (MM BTU/Hr)	Steam (MM BTU/Hr)
Feed	0.3	1.3
Pretreatment	5.5	56.3
Enzyme Production	18.1	----
Hydrolysis Reactor	8.3	----
Fermentation	2.0	5.0
Ethanol Purification	9.5	42.0
Offsite Tankage	0.8	----
Waste Treatment	0.6	182.0
Utilities	11.0	7.1
Miscellaneous	4.0	11.0
Totals	60.1	304.7

For the base case Iogen plant operating at full capacity:

Power generated = 28.8 megawatts
Power consumed = 17.6 megawatts
Excess power = 11.2 megawatts

The Iogen process has demonstrated, by far, the best economic potential of any wood-to-ethanol process documented to date, acid or enzymatic hydrolysis! The estimated ethanol production cost was 48.04 cents per liter in Canadian dollars, which translates to about $1.63 per gallon in U.S. dollars. These results were generated with no by-product credits.

7 Sensitivity Analyses

The computer-base model was used to evaluate analytical relationships between process and cost parameters and the selling price of ethanol. Sensitivity analyses were completed for 15 parameters important to the economic improvement of the Iogen process. The results of these analyses are discussed in the following sections along with graphs which illustrate the trends for each parameter. An assessment of the relative importance of each variable is included and the degree of interaction of each with other parameters is discussed.

The sensitivity analyses are divided into two general areas: technical process parameters, and design and economic parameters. The technical process parameters refer to the physical and chemical changes occurring during the process operation. The design and economic parameters refer to assumptions associated with the cost and the quantity of material flows into and out of the plant.

7.1 Technical Process Parameters

The technical process parameters are the physical and chemical characteristics whose changes will effect changes to the system performance and thereby modify the economic performance of the system. The base case value for each of these parameters and their process impact is listed in the following sections:

7.1.1 Enzyme Loading

Enzyme loading is the amount of enzyme [in International Units (I.U.)] used per gram of cellulose in the hydrolysis reactor. This is a very important factor in any enzymatic hydrolysis process since it determines the total amount of enzyme required and thus, to a large extent, the size and total cost of the enzyme production section of the facility. Figure 4 shows the relationship between enzyme loading and ethanol price for the Iogen process.

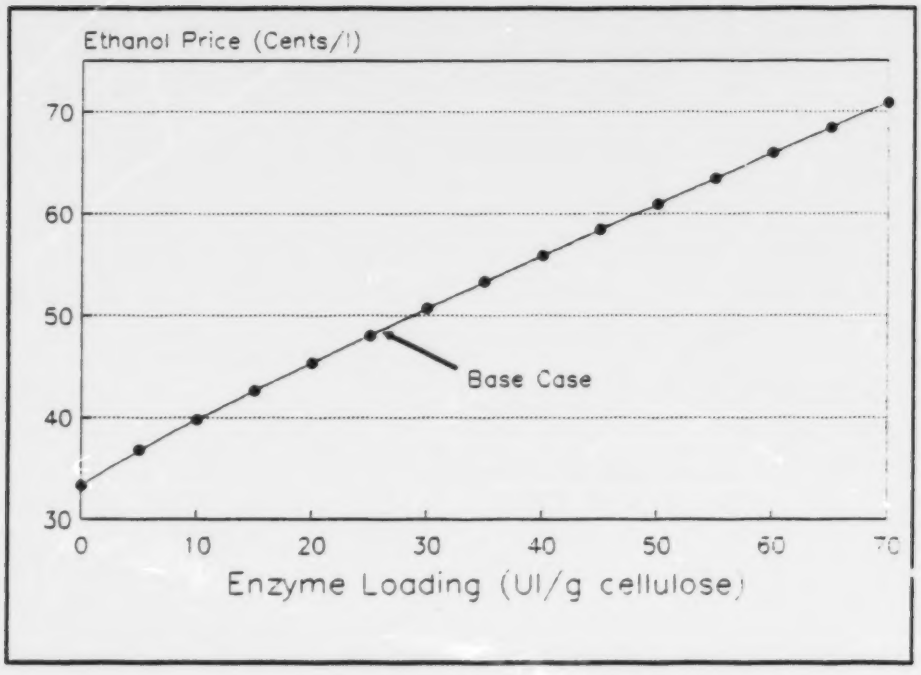

Figure 4. Enzyme Loading versus Ethanol Price

The process costs are highly sensitive to enzyme loading. The increase in capital and operating costs due to increased enzyme loading cause the ethanol price to rise from 34 cents per liter at 0 loading to 75 cents per liter at 70 I.U. per gram of cellulose. The base case process assumption of 25 I.U. per gram of cellulose yields an ethanol price of 48.04 cents per liter. If no enzyme were required to effect the hydrolysis and all the other process conditions remained the same, then the ethanol price would drop to about 34 cents per liter. This value is a theoretical limit to the impact that the enzyme section of the process can have on the price of ethanol, as long as the principal configuration and other operating conditions of the process remain the same.

In practice, lower enzyme loading or lower enzyme production cost would change the plant operating procedures. This would lower the cost of enzyme which would allow a reduction in hydrolysis time and an increase in the glucose concentration, both of which reduce the capital costs and energy costs for the plant. The net impact of these parameters could reduce the ethanol price to the range of 15 to 20 cents per liter.

The enzyme productivity data in Section 7.1.1 is an excellent example of this effect: it shows that the required ethanol selling price approaches a limit as enzyme productivity increases. This suggests that without significant changes in the processing procedures, increasing enzyme productivity rate will not improve the process economics significantly at about 1000 I.U. per liter per hour and above.

Enzyme loading could be reduced if a better pretreatment process could be developed that rendered the substrate in a more amorphous condition. A second method would be to increase the activity of the enzyme complex through genetic manipulation.

7.1.2 Enzyme Productivity

Figure 5 shows the impact of enzyme productivity on ethanol price over a range of 50 to 1600 I.U. per liter per hour. Enzyme productivity, or the rate of enzyme production, is defined as the units of enzyme produced (in I.U.'s) per unit of fermenter volume per hour. The base case value used for enzyme productivity was 400 I.U. per liter per hour.

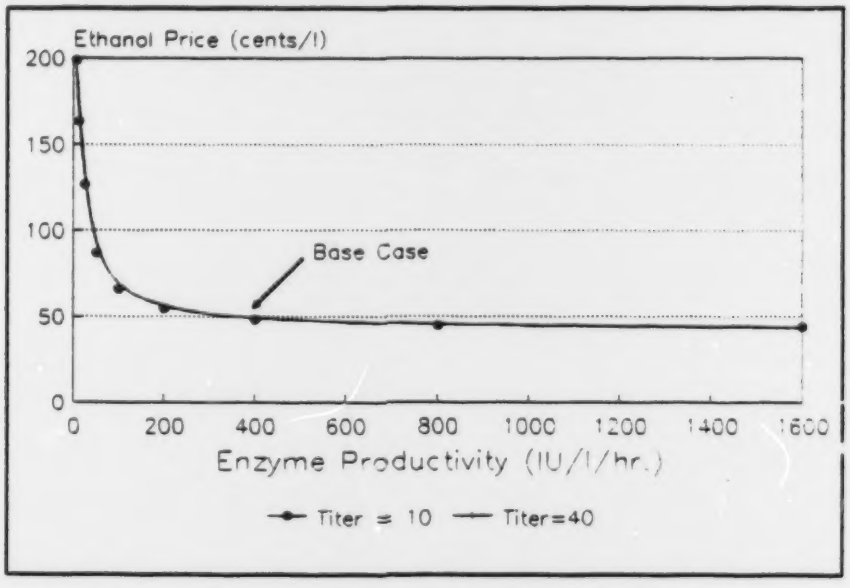

Figure 5. Enzyme Productivity versus Ethanol Price

Processes that use cellulose as the carbon source for enzyme production have achieved enzyme production rates in the range of 50 to 100 I.U. per liter per hour, with the consequent ethanol production cost of about $1.50 to $2 per liter. The high productivities observed in the Iogen process have been achieved with lactose sugar, a liquid substrate, used as the carbon source for enzyme growth. This is a one of the most critical technical parameters in terms of economic impact. Improvement is enzyme productivity reduce capital cost and operating cost by requiring smaller tankage for enzyme growth and reducing the amount of electrical energy for stirring and aeration.

The base case value for enzyme productivity is 400 I.U. per liter per hour at an enzyme titer of 40 I.U. per milliliter. The ethanol price is 48.04 cents per liter. If the titer is reduced to 10 I.U. per milliliter and the titer maintained at 400 I.U. per liter per hour the ethanol price increases to about 48.26 cents per liter. This is a relatively small increase in ethanol price for a fourfold decrease in enzyme concentration in solution. A similar decrease in the enzyme productivity, from 400 to 100 I.U. per liter per hour would cause the ethanol price to increase to over $1.00 per liter.

However, in the overall evaluation of the Iogen process the high enzyme productivity is both a major strength and a possible weakness. The lack of suitable volumes of lactose sugars to supply more than a few commercial scale plants could constrain the commercial potential for this technology. This issue is discussed further in Section 10.1.

7.1.3 Enzyme Titer

Enzyme titer is the concentration of enzyme in the production growth media expressed in international filter paper units per milliliter of broth. A filter paper unit is approximately one milligram of protein, therefore, a titer of 40 equals 40 milligrams of protein per one milliliter of solution. If all the protein is active enzyme then this translates to 400 I.U. per liter. The results in Figure 6 show that enzyme titer is not a major economic driver in enzymatic systems, if it is measured at constant productivity. The effects of enzyme titer on ethanol price at fixed time and at constant productivity are shown in Figure 6.

The base case values of 400 I.U. per liter per hour productivity and 40 I.U. per milliliter titer occur at the intersection of the two curves. Another value for the constant productivity level would produce a similar relationship, and a curve parallel to the constant productivity line in Figure 6.

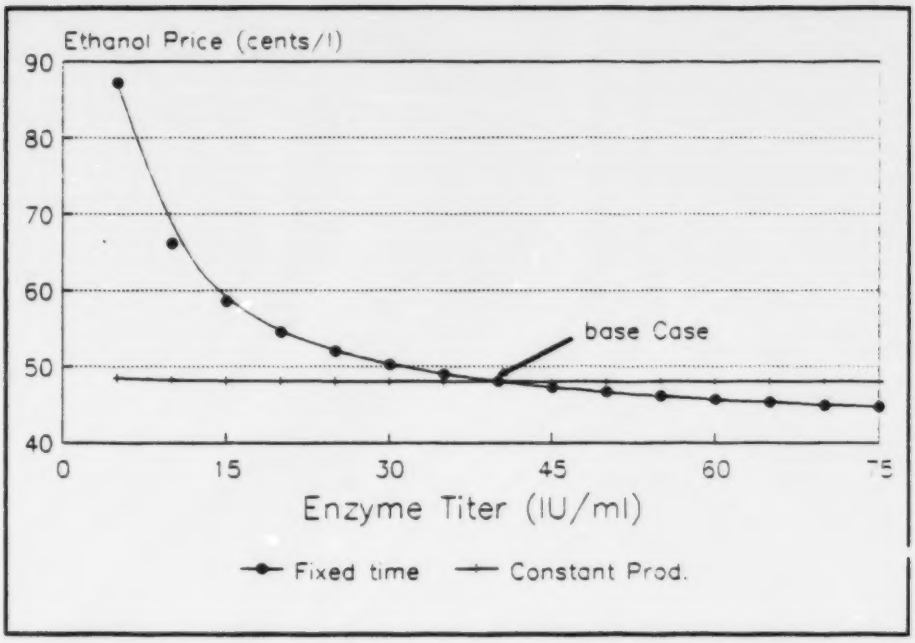

Figure 6. Enzyme Titer versus Ethanol Price

The conventional method to measure the impact of enzyme titer on processing is to hold all process variables constant and vary the titer over some specified range of values. When analyzing this experiment The effect of titer in the simulation model, the enzyme production time is also held constant. The fixed time curve in Figure 6 shows the result of this experiment. Here it appears that enzyme titer has a large impact on the process economics. However, the enzyme productivity also changes during this series of calculations, varying from 50 to 750 I.U. per liter per hour as the titer varied from 5 to 75 I.U. per milliliter. This effect is seen in the curve labeled fixed time.

The same analysis was run using a constant productivity of 400 I.U. per liter per hour. If we used a wide range of titers, at constant productivity, we would see that titer has only a small impact on ethanol price. We can conclude from this result that enzyme titer is not a significant economic driver in this process. This finding is not common knowledge in the technical community, since most (real) experiments are not run in the context of a process system, and these types of interactions cannot be easily evaluated.

7.1.4 Enzyme Yield

Enzyme yield is the amount of enzyme that can be produced from one gram of the carbon source used to grow the enzyme. In the Iogen process design, the carbon source is lactose. Figure 7 shows the impact of enzyme yield on ethanol price. The base case value for enzyme yield is 250 I.U. per gram of lactose.

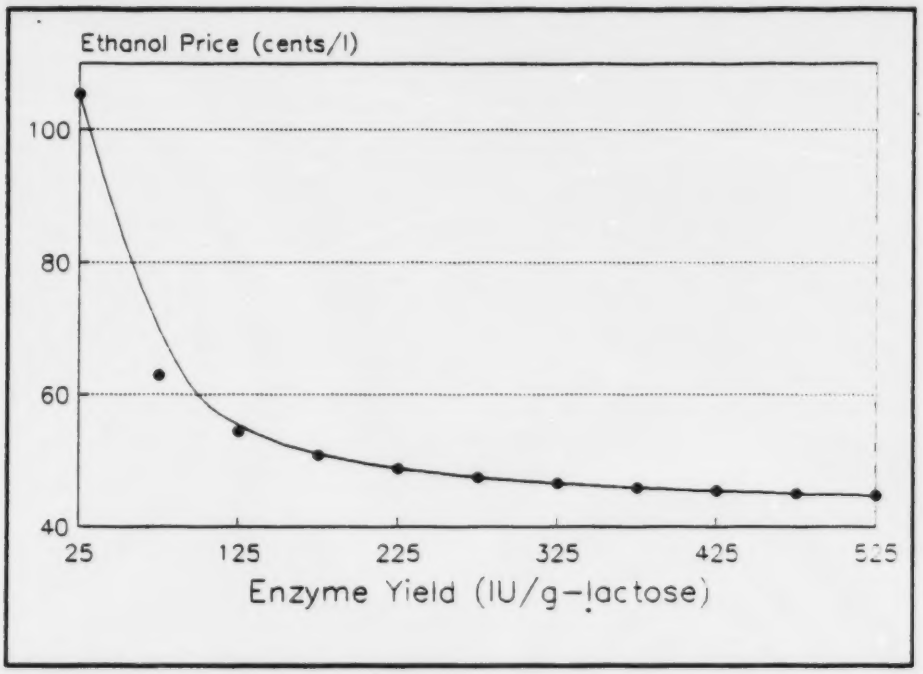

Figure 7. Enzyme Yield versus Ethanol Price

The amount of lactose required for the process is, to a large extent, determined by enzyme yield in combination with the total amount of enzyme required for the process. The scale of the enzyme section of the plant is also impacted by enzyme yield and, therefore, the capital cost of the enzyme section. Increasing the enzyme yield to 500 I.U. per gram of lactose would reduce enzyme production capital cost and the amount of lactose required and thus reduce the required selling price of ethanol by 4 cents per liter to 44 cents per liter.

7.1.5 Solids Loading

In cellulose processing, solids loading is the percent of total solids in the hydrolysis reactor used to produce glucose prior to fermentation. The cellulose content of the reactor solids was Figure 8 shows the relationship between percent solids in the hydrolysis reactor and the resultant ethanol price.

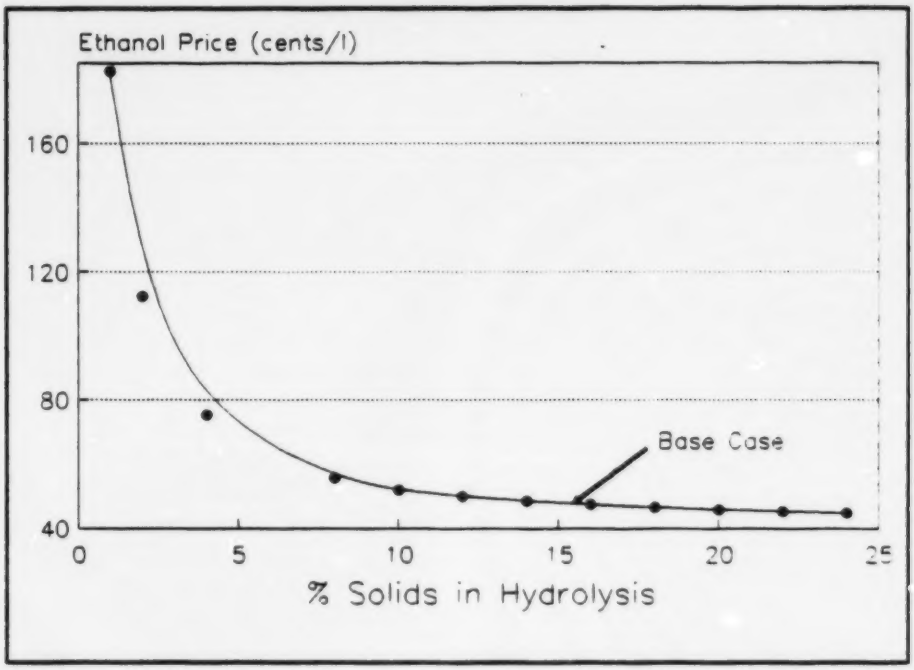

Figure 8. Solids Loading versus Ethanol Price

The base case process was constructed using 15 percent solids in the hydrolysis reactor. The resultant ethanol price was 48.04 cents per liter. At 10 percent solids loading the ethanol price increased to about 58 cents per liter, while at 20 percent solids loading, the price decreased to about 43 cents per liter. Very dilute slurries increase the ethanol price dramatically due to additional downstream water processing, which increases capital cost and energy costs.

7.1.6 Hydrolysis Time

Hydrolysis time is the time required to reach a desired level of glucose yield. The optimum value of hydrolysis time is determined

by the interaction of several process variables. Mainly, these relationships are determined experimentally and include the effect of pretreatment, enzyme loading, temperature and end-product inhibition. Figure 9 shows the relationship between hydrolysis time and ethanol price. The principal economic impact of changes to the hydrolysis time is on the capital cost of the hydrolysis reactors and the energy for stirring the hydrolysis media. If the hydrolysis time is reduced the required size or number of hydrolysis reactors is reduced, and thus, the capital cost.

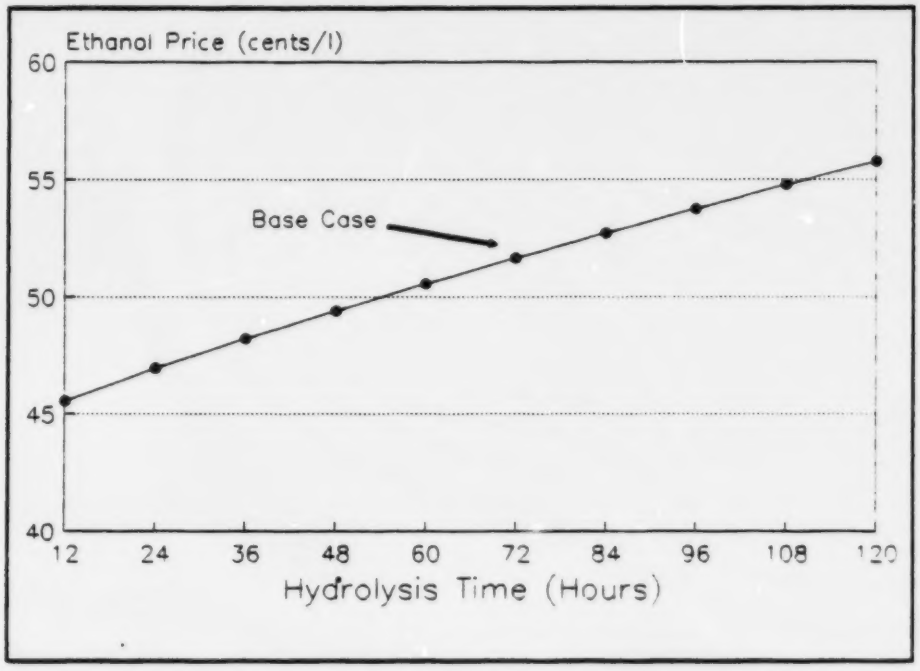

Figure 9. Hydrolysis Time versus Ethanol Price

The hydrolysis time used in the base case was 72 hours. With the pretreatment and enzyme loading of the base case process, the hydrolysis yield of glucose was 85 percent.

It should be noted that the process economics are relatively insensitive to hydrolysis time; for example, the ethanol price varied from 44.7 cents per liter to 50.5 cents per liter as the hydrolysis time changed from 12 and 120 hours and the remaining process variables held constant. This parameter provides an area for trade-off to be evaluated, e.g., varying the hydrolysis time and enzyme loading to find an economic optimum among these variables.

7.1.7 Hydrolysis Yield

Hydrolysis yield is the percent yield of potential glucose obtained from the cellulose fraction of the feedstock entering the hydrolysis reactor. The base case yield was 85 percent obtained in 72 hours.

The process economics are very sensitive to hydrolysis yield as can be seen in Figure 10. The ethanol price will vary between 79 and 41 cents per liter as the hydrolysis yield changes from 50 percent to 100 percent. The principal cause for this reduction is the requirement for less feedstock going into the plant and reduction in the energy and capital costs for the waste treatment section of the plant.

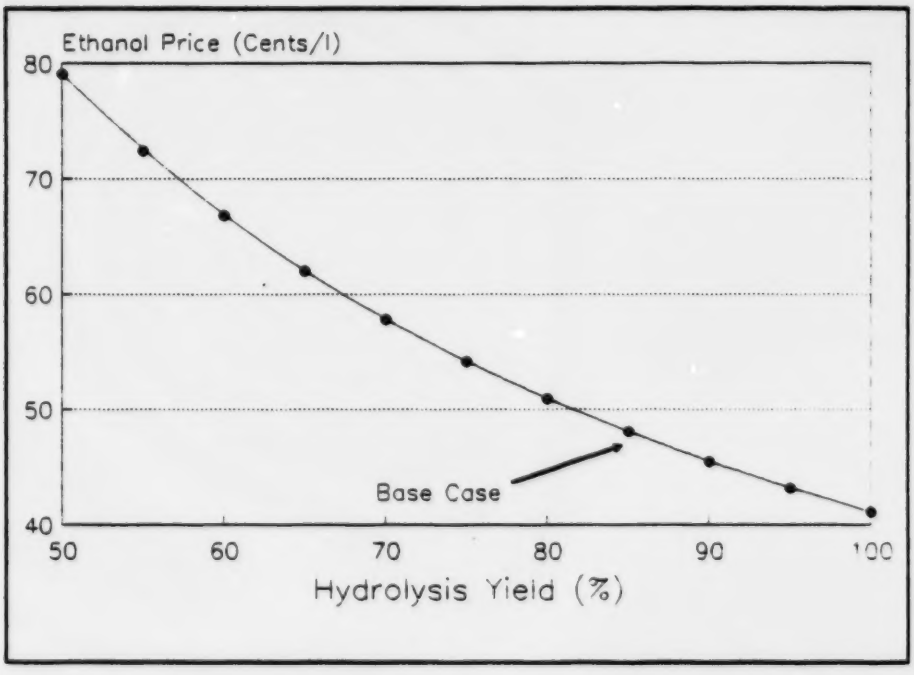

Figure 10. Hydrolysis Yield versus Ethanol Price

The hydrolysis yield is also a variable that is effected by several other parameters (i.e., hydrolysis time, solids loading in the hydrolysis reactor, enzyme loading and enzyme end-product inhibition, and temperature). Pretreatment also impacts the rate of hydrolysis. However, at present, a good analytical relationship among this set of parameters and the glucose yield does not exist. Empirical data is used to define the interactions, and computer modeling is used to simulate the effects.

7.2 Design and Economic Parameters: Input and Output Assumptions

The design and economic parameters form a group of input and output controls for the process. These parameters set the scale of the process, the feedstock costs, and the value of the co-products. The co-products will require modification of the plant operation from the base case design, whereas the rest of these parameters do not impact the base process operation.

7.2.1 Plant Scale

Fixing the operating parameters and varying the plant scale illustrate the sensitivity of the process to scale factors. At a scale of 100 tonnes per day, the required ethanol selling price was about 78 cents per liter; if the scale was increased to 1000 tonnes per day (the base case plant size), the ethanol price drops to 48.04 cents per liter. Extending the scale to 2000 tonnes per day further reduces the ethanol price to 44 cents per liter. Figure 11 shows the effect of plant scale on ethanol price.

The principal reason for the scale effects is that the factors that calculate capital costs and manpower costs for the plant are not linear with scale. That is, when the plant size is reduced by a factor of 10 (1000 to 100 tonnes per day), the capital and manpower costs are reduced by a factor of about 5.

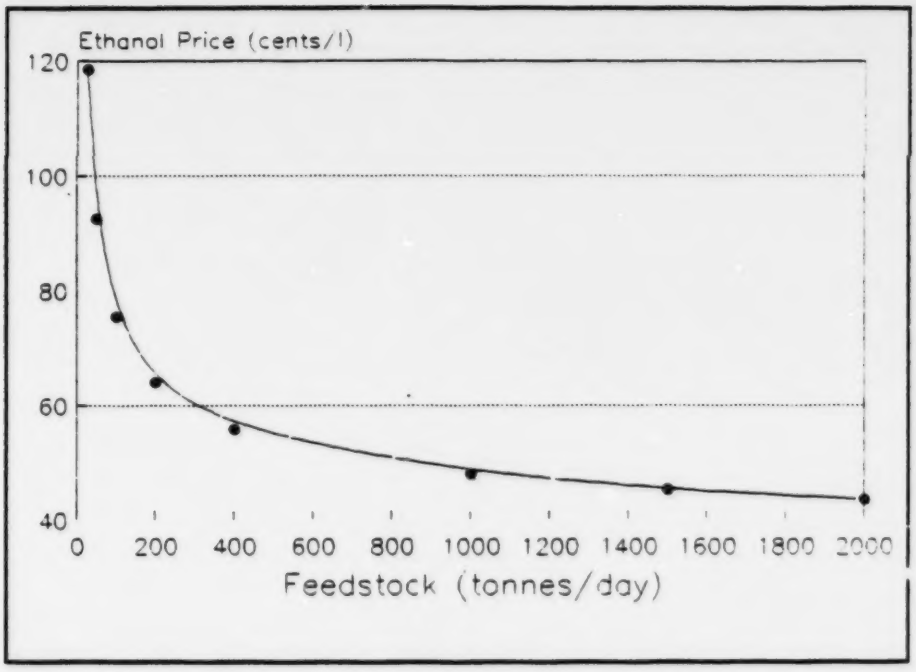

Figure 11. Plant Scale versus Ethanol Price

7.2.2 Feedstock Cost

The Iogen process has two principal streams that provide the feedstocks for the process. The first is the wood feed stream, which is the source of the cellulose, lignin and molasses; the second is lactose (cheese whey), which is the carbon source for enzyme production.

Figure 12 shows the impact of the cost of wood on the ethanol price in the base case process design. The base case value is 4.2 cents per kilogram (or $42 per tonne). As the feedstock cost is changed from 0 to 8 cents per kilogram (0 to $80 per tonne), the ethanol price varied between 33 cents per liter and 62 cents per liter.

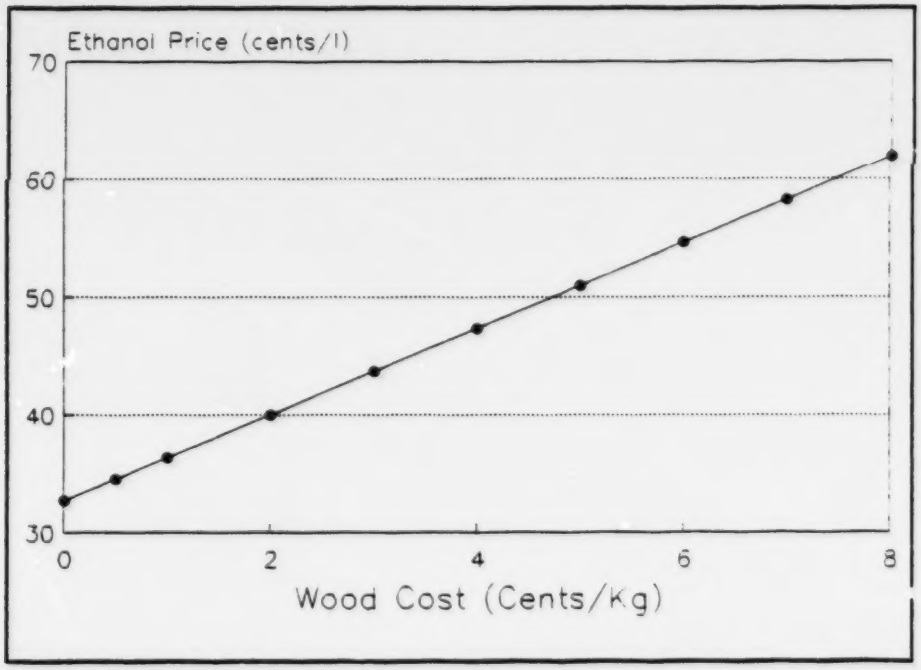

Figure 12. Wood Costs versus Ethanol Price

Figure 13 shows the impact of the cost of lactose on the price of ethanol in the base case process. The base case value for lactose was 23 cents per kilogram. Figure 13 was generated by fixing base case design parameters and allowing the cost of lactose to vary from 0 to 50 cents per kilogram. The ethanol price varied from 44 to 52.5 cents per liter.

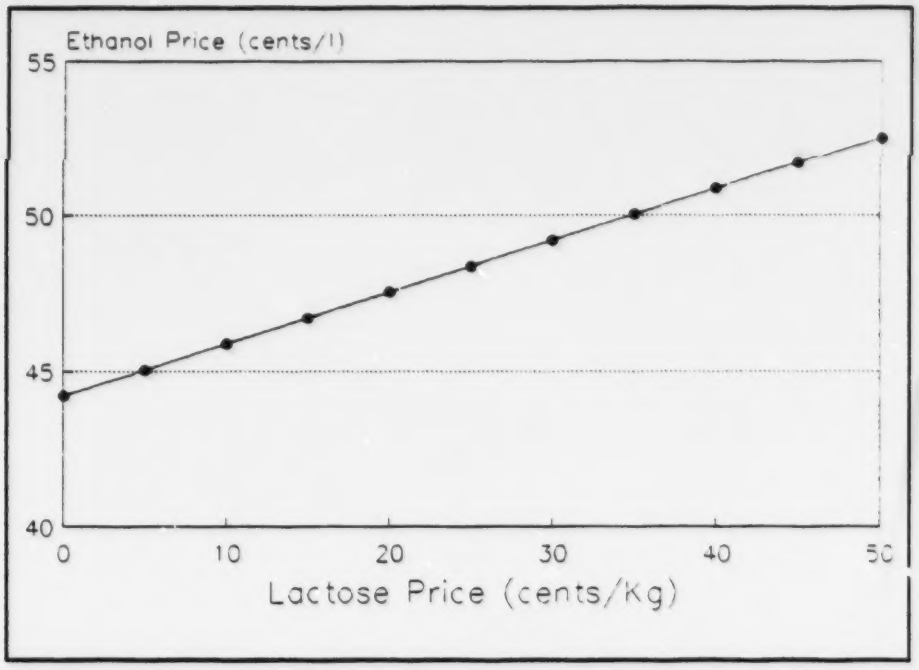

Figure 13. Lactose Cost versus Ethanol Price

The price of lactose is not a major economic concern in the process based on its cost alone; however, the process economics are strongly driven by enzyme productivity (as mentioned earlier) and its importance to the process cannot be minimized. The Iogen process and its apparent high economic potential are due in no small measure to the high rate of enzyme productivity. Without lactose as the carbon source for enzyme production, the current best alternative technology is nearly an order of magnitude less efficient at producing cellulase enzyme. The importance of this impact will be reviewed in detail in Section 10.1.

7.2.3 Lignin Price

In the definition of the base case process lignin was not used as an external by-product but instead was used to provide fuel for heat, steam and electricity needed in the process. If, however, the lignin stream is collected and assigned a value as a co-product of ethanol production, it has a very large impact on the economics of the ethanol facility. Figure 14 shows the potential impact of lignin as a co-product.

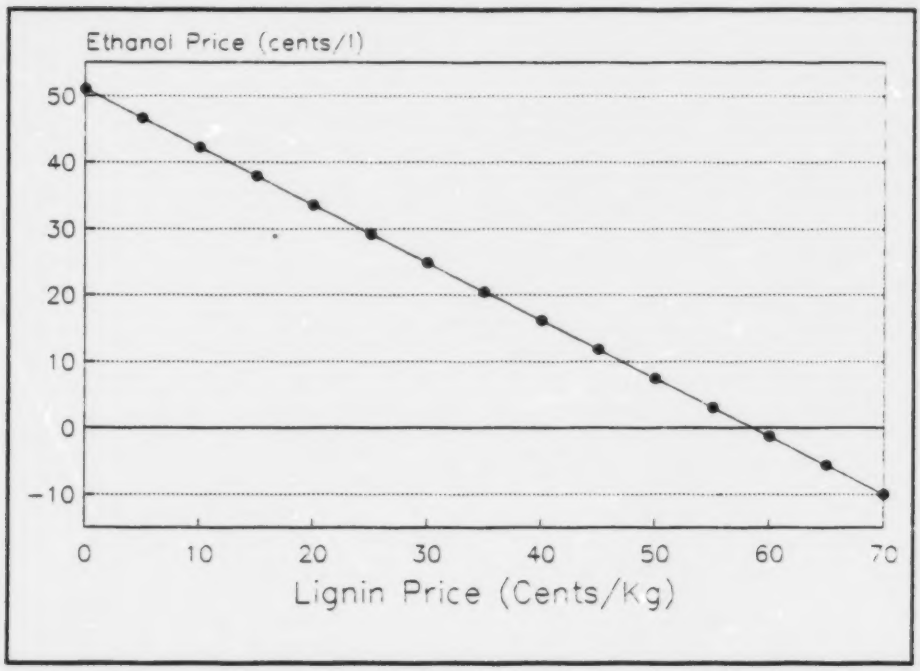

Figure 14. Lignin Value versus Ethanol Price

As the price of lignin varies from 0 and 80 cents per kilogram, the required ethanol selling price changes from +51 to -10 cents per liter. Removing the lignin from the process reduces the residual materials used to generate the process heat and electricity. In the base case this amounts to about 3 cent per liter credit or the approximate fuel value for lignin.

This suggests that if lignin can be sold at the higher values and in large volume, then ethanol might well become the co-product. In fact, a grassroots lignin plant might do quite well without any ethanol production needed for profitable operation.

7.2.4 Molasses Price

Molasses is not included as a co-product in the base case process design because it does not demonstrate, base on the simulation, the economic potential shown with lignin recovery. The range of co-product values for the molasses price is not as broad as the range for lignin. Figure 15 shows the potential impact that the molasses price could have on the required ethanol selling price.

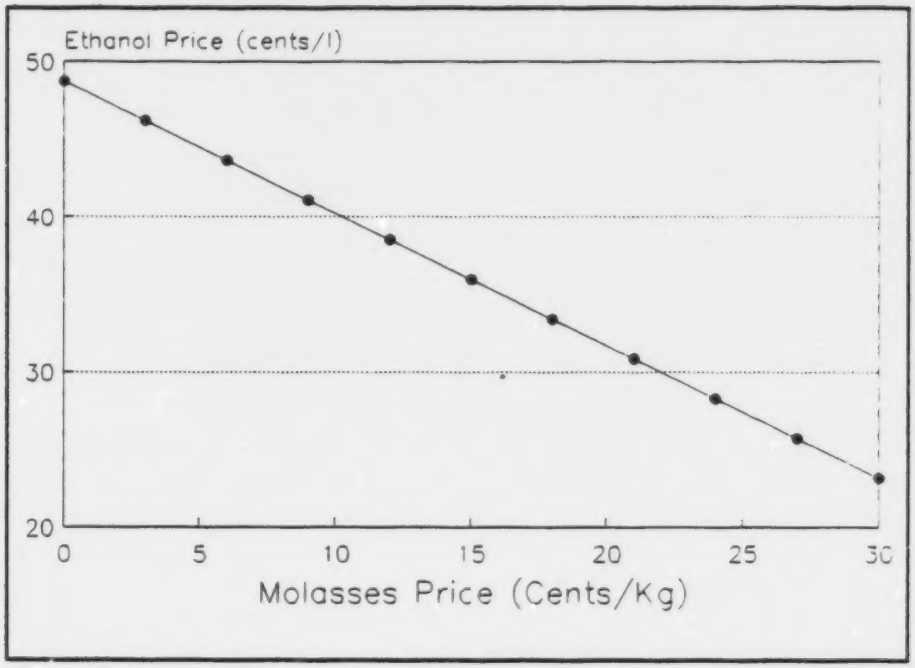

Figure 15. Molasses Value versus Ethanol Price

The ethanol price changed from 48 to 24 cents per liter as the value for molasses varied from 0 to 30 cents per kilogram. The most probable value for molasses is 12 cents per kilogram or $120 per tonne, which is the approximate price molasses would demand as a carbohydrate source in animal feed supplements. This price reduces the ethanol selling price from the base case by 10 cents per liter to 38 cents per liter.

The market value for molasses as an animal feed is very volatile and the value can easily vary from $40 to $140 per tonne.

7.2.5 Electricity Price

The waste streams, i.e., the unhydrolyzed carbohydrates, residual lignin and other waste materials, from the process are dried to 50 percent moisture and used to produce the required processing energy in the form of steam and electricity. Figure 16 shows the impact of electricity selling price or purchase cost on the ethanol price.

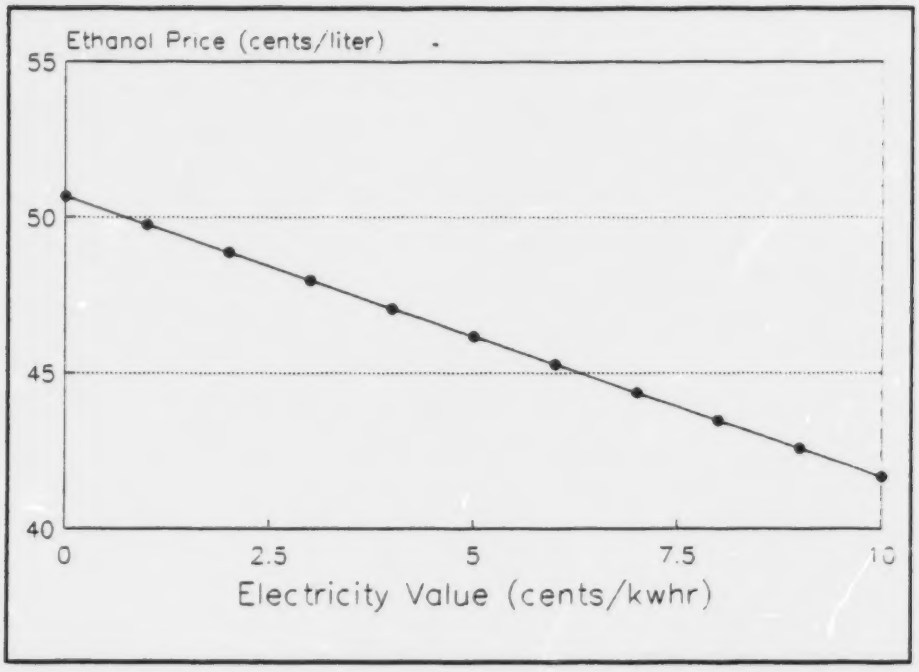

Figure 16. Electricity Value versus Ethanol Price

In the base case, an excess of electricity is produced and is assigned a value equal to the cost for generation. That cost is about 3 cents per kilowatt- hour. This option is of varying value, since the cost of electrical energy is very different in various locations in Canada. However, this approach does make the facility self-sufficient in energy and in a position to sell excess energy.

If the electrical energy is purchased, the capital cost for the steam generators would be deleted from the capital cost of the plant and reduce the base case capital costs by $10 million. This would reduce the ethanol price about 1.4 cents per liter assuming electricity can be purchased at 2.92 cents per kwh. The ethanol price shows a sensitivity of 9.2 cents per liter for a 0 to 10 cent per kilowatt-hour selling price of the excess electricity, going from 50.7 to 41.5 cents per liter.

7.2.6 Capital Costs

The capital cost of the base case plant was estimated using several sources of data on equipment costs. However, this estimate could fluctuate by as much as 25 percent, particularly because of the inflation adjustment values used to adjust the year base for the

cost estimate. The ICARUS estimate used to generate the base case capital costs is accurate to a range of minus 0 and plus 25 percent. Figure 17 shows the impact of varying the capital cost of the plant in increments of 10 percent above and below the base value.

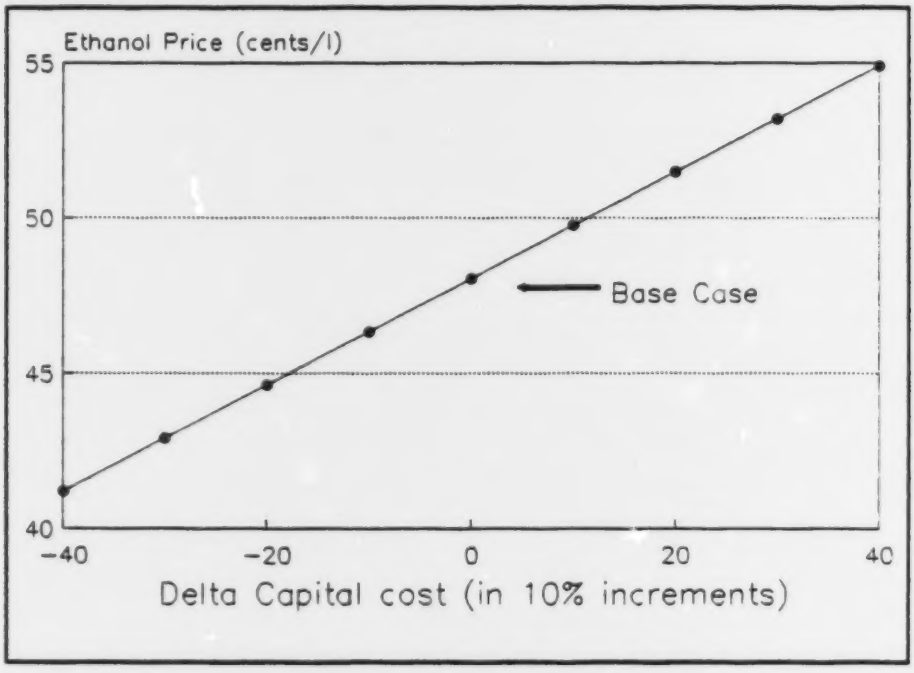

Figure 17. Capital Cost versus Ethanol Price

The ethanol price varies from 41 to 55 cents per liter as the capital costs varies from -40 percent to +40 percent of the base case value.

The data for the Figure was obtained while all of the other operating parameters were held constant at the base case values. Also, running the test required that the maintenance and manpower factors be uncoupled from the capital costs. (Normal operation of the model couples these factors, since higher capital costs imply a larger plant with more manpower requirements.)

7.2.7 Capital Recovery Factor

The annual capital recovery factor has a substantial effect on the annual capital charges and therefore has an impact on the required ethanol selling price.

Figure 18 shows the effect of varying the capital recovery factor (CRF) on the ethanol price. As the CRF is varied from five percent to 40 percent, the ethanol price went from 39 cents per liter to 89 cents per liter.

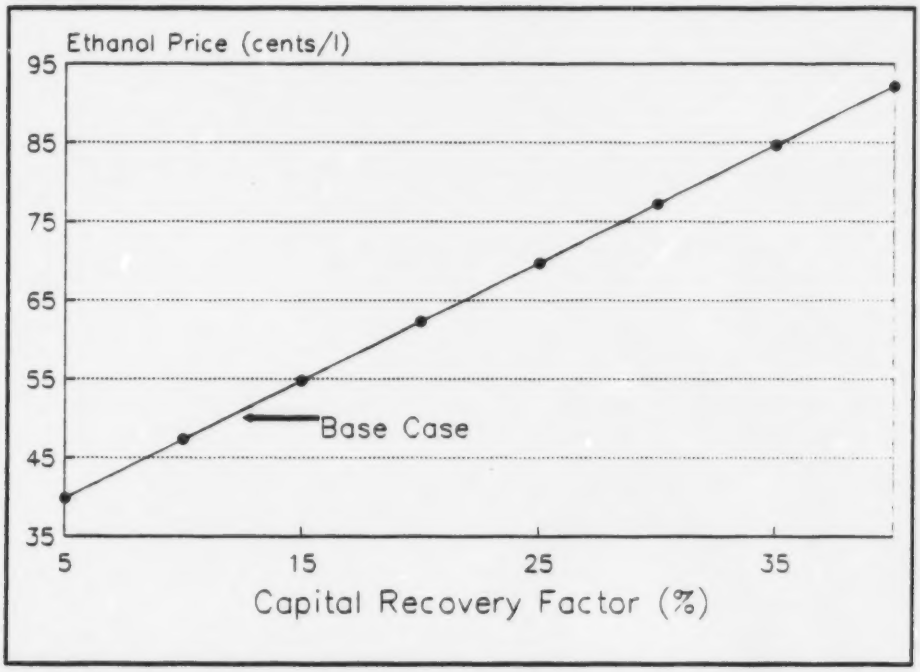

Figure 18. Capital Recovery Factor versus Ethanol Price

A commercial-scale plant can be financed in one of several different ways: government, utility and private sector. Government and public utility financing can be arranged at nominal rates between 8 and 12 percent; private utility financing will run 12 percent to 18 percent depending on the size, technology and risks; and private financing will run from 15 percent to as high as 30 percent and more for high-risk projects. Obviously, the method chosen for financing a commercial-scale plant will have a significant impact on the required product selling price. (These curves were generated without the benefit of co-product credits.) Other factors such as debt to equity ratio will have to accounted for in a thorough economic analysis.

This single factor has one of the highest impact on the required ethanol selling price and emphasizes the necessity to consider the method of financing a plant when calculating the economic performance.

7.3 Sensitivity Analysis: Summary

The results from the sensitivity analyses are summarized in Table 4 and Table 5, containing the outputs from the technical process parameters, and the process design and economic parameters, respectively. The tables show the high and low values, in cents per liter, for each parameter, and the change (delta high and low) from the base case value of 48.04 cents per liter. If the delta values are summed, the technical process parameters total varies from -37.68 cents per liter to $1.41 per liter, and the design and economic parameters total varies from -$1.24 per liter to 89.9 cents per liter.

Table 4. Effect of Variation in the Technical Process Parameters on Required Ethanol Selling Price.

Variable Name	low	high	Delta Low	Delta High
Enzyme loading	33.00	71.00	-15.04	22.96
Enzyme prod.	44.00	90.00	-4.04	41.96
Enzyme titer	47.80	48.70	-0.24	0.66
Enzyme yield	44.00	65.00	-4.04	16.96
Hydrolysis time	44.80	50.40	-3.24	2.36
Hydrolysis	41.00	77.00	-7.04	28.96
Solids loading	44.00	75.00	-4.04	26.96
Sum of Changes			-37.68	140.82

Table 5. Effect of Variation in the Process Design and Economic Parameters on the Required Ethanol Selling Price.

Variable Name	low	high	Delta Low	Delta High
Plant scale	43.00	58.00	-5.04	9.96
Wood cost	33.00	62.00	-15.04	13.96
Lactose cost	44.20	52.50	-3.84	4.46
Electricity	41.80	50.60	-6.24	2.56
Lignin price	-10.00	51.00	-58.04	2.96
Molasses price	23.00	48.04	-25.04	0
Capital cost	41.30	55.00	-6.74	6.96
Capital recov.	44.00	97.00	-4.04	48.96
Sum of Changes			-124.00	89.82

The sensitivity analyses are very useful for identifying the key parameters with the highest economic impact on the required ethanol selling price. The analysis process can be further refined to show the potential improvements to the base case process economics expected via technical and design modifications. The results of the refined analyses are shown in Figure 19 and Figure 20. In this case, the summed improvements in the technical process parameters totals -25.9 cents per liter and the summed result for design and economic parameters totals - 36.4 cents per liter in the required ethanol selling price.

In figures 19 and 20 the initial on the x-axis refer to the variables used in tables 4 and 5, i.e., EL means enzyme loading, EP means enzyme productivity, etc.

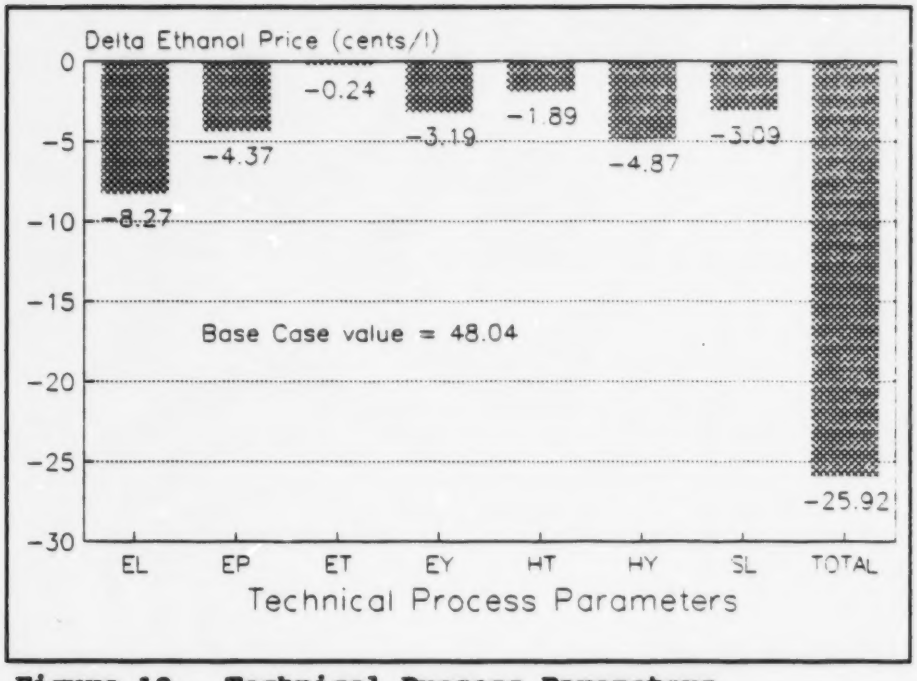

Figure 19. Technical Process Parameters

Inspection of Figure 19 shows enzyme loading to be the dominant technical process parameter in driving down the ethanol price. Enzyme productivity, enzyme yield, hydrolysis yield, and solids loading are the other significant parameters.

Figure 20 shows the impact of the design and economic parameters and illustrates the significant potential of plant scale, wood cost, lignin value, molasses value, and capital recovery factor to reduce the ethanol price. Lignin value dominates this group of parameters.

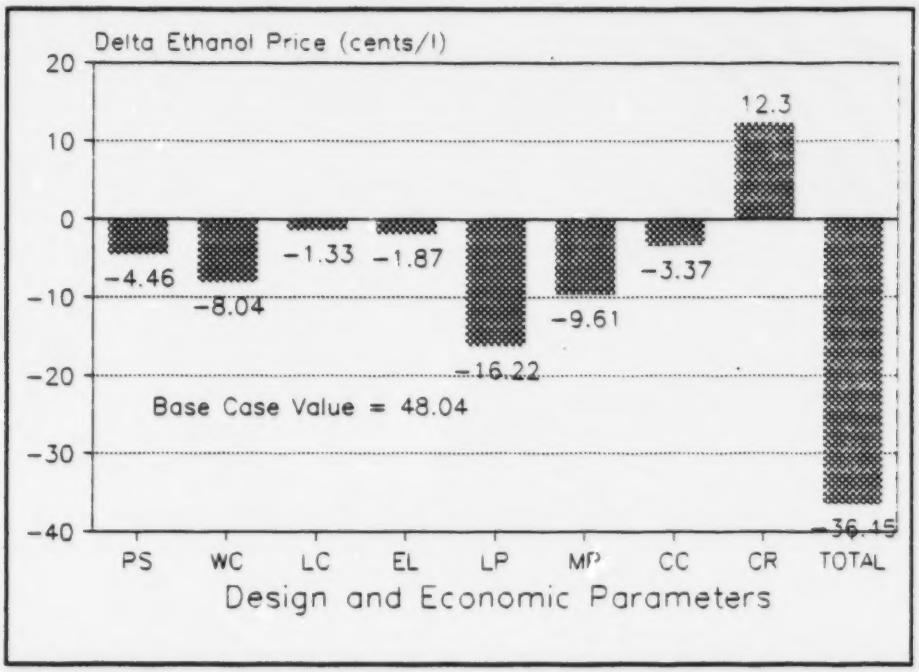

Figure 20. Process Design and Economic Parameters

It is significant to note the positive value for the capital recovery factor (CRF). This positive value occurred because the base case design uses 12.9 percent as the CRF, i.e., government financing as the basis. It is assumed that a commercial plant will require private sector financing, in which case the CRF could be as high as 25 percent or more. In Figure 20 a value of 25 percent was used.

While these analyses show the relationships between the various parameters and the required ethanol selling price and can be used to identify the key economic drivers in the process, it fails to show interaction between the parameters and does not permit including the uncertainty in attaining the specified goal. In Section 8, the concept of Monte Carlo simulation is introduced and will permit the interactions among the variables to be factored into the analysis and also permit the assignment of uncertainty into the analysis.

Monte Carlo simulation uses the key parameters identified through the sensitivity analyses.

8 Monte Carlo Simulations

A question frequently asked is: Why use Monte Carlo simulation instead of simpler tools such as sensitivity analysis, CPM (critical path method) or PERT (performance evaluation and review technique)? CPM and PERT are tools designed for schedule and cost analysis and do not provide forecast and risk analysis capability. Sensitivity analysis provides forecasting limited to one or two dimensions, but has no mechanism to directly assess the risk or uncertainty in the analysis. Monte Carlo simulation provides a method for completing multidimensional analysis and factoring into the analysis uncertainty in the form of a probability function.

The sensitivity analyses described in the previous section illustrate the multi-variable nature of the Iogen process (i.e., that the process is dependent on several variables and, in some cases, these variables are interdependent). The combined effect of these variables is not an additive function of the economic output of the process and, therefore, we can use Monte Carlo simulation as a tool to show the impact of using several variables, and then account for the uncertainty of the variables and, at the same time, the interdependence among the variables.

The variable names and mean values used in the Monte Carlo simulation are listed in Tables 6, 7 and 8, along with the standard deviation values for each. The mean value is the expected value for each parameter and the standard deviation is the confidence level attached to each parameter. A standard deviation of 0 would indicate certainty in the variable, while one standard deviation of the mean value would include 67 percent of the measured population, and at two standard deviations, 95 percent of the population would be included. The expected value from a Monte Carlo simulation is the fifty percent level (or 0.5 cumulative probability point) on the output figure. This is the mean value from the simulation and, in a mathematical sense, the probability of obtaining results on either side of this value has equal weight.

These values were not determined by an exact science, and therefore do not provide a quantitative, analytical measure of the future performance of a new process. However, the cumulative effects of uncertainty used to generate the Monte Carlo results do provide a good qualitative sense of possible variability in the analysis results and a sense for the potential for future performance improvements.

8.1 Standard Process Simulation

The major breakthrough of the Iogen process compared to conventional approaches to enzymatic conversion of cellulose to ethanol is the dramatic improvement is enzyme production based on the use of lactose as the carbon source for cellulase production. The conventional process uses cellulose as the carbon source for growing the enzymes. The productivity in conventional systems is in the range of 50 to 100 I.U. per liter per hour. From the results of the sensitivity analysis given earlier, observers can easily see the economic penalty one pays due to a four- to eightfold decrease in enzyme productivity. There are physical and process related reasons for this difference which will be discussed in Section 10.

A hypothetical standard case was developed using the parameters from a conventional process. The conventional process was developed by selecting the best data available in the technical literature on cellulose hydrolysis and cellulase production using cellulose. A Monte Carlo simulation run was conducted for this design. The input parameters are shown in Table 6.

Table 6. Monte Carlo Simulation: Standard Process

Variable	Mean Value	Standard Deviation
Enzyme loading	45 (IU/g)	4.5
Enzyme prod.	100 (IU/l/h)	10.0
Glucose yield	73 (%)	3.5
Solids loading	10 (%)	1.0
Hydrolysis time	72 h	7.2

Figure 21 shows the output from this simulation with an expected ethanol price of $1.10 per liter. This is more than a twofold increase over the base case Iogen process design.

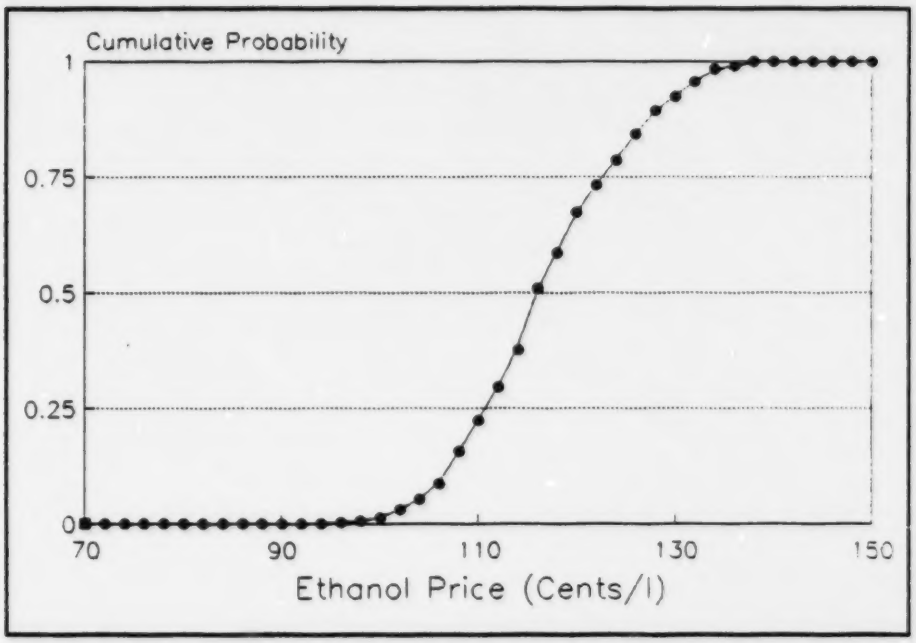

Figure 21. Monte Carlo Simulation: Standard Case Design

In addition to the difference between the standard (conventional) design and the Iogen base case in enzyme productivity, there are significant differences in enzyme loading, solids loading, and glucose yield. The values used in the standard design are typical of the values reported in the literature for similar systems. Enzyme loading in the standard base case is 30 I.U. per gram of solids in the hydrolysis reactor. Since the lignin is included in the solids and accounts for approximately one-third of the mass, the net enzyme per gram of cellulose is about 45 I.U.

The glucose yield is a complex function of the enzyme loading, solids loading in hydrolysis and the hydrolysis time. The most comprehensive data in the literature is provided by Dekker (Dekker 1983). In that report, he demonstrated that when using steam-exploded Bagasse and Eucalyptus wood at a constant hydrolysis time of 48 hours, the glucose yield was proportional to enzyme loading and the solids content of the reactor.

The paper also showed the beta-glucosidase supplementation greatly enhanced the hydrolysis rate and that lignin tended to adsorb the beta-glucosidase. Thus, the optimum rate of hydrolysis is affected by residual lignin in the pretreated pulp. Dekker's research was

done on different feedstocks than the steam-exploded aspen used in the Iogen process, however, the generalities found in his work should be applicable.

The optimum values from Dekker's paper suggest that an enzyme loading of 45 I.U. per gram of cellulose and 10 percent solids in the reactor would produce a 73 percent glucose yield in 72 hours. (These are the values chosen for use in the standard case.) Contrast these values to the Iogen base case design values of 25 I.U. per gram of Cellulose, 15 percent solids loading and 85 percent glucose yield in 72 hours.

Reference to the impact of removing lignin before hydrolysis is made in Section 10.

8.2 Iogen Base Case Simulation

The base case process was evaluated via Monte Carlo simulation with and without a co-product credit for lignin. Table 7 lists the variables and values used for the base case run. Case one was run with the co-product lignin out of the system and case two with lignin credit included.

Table 7. Monte Carlo Simulation: Iogen Base Case

Variable	Mean value	Standard Deviation.
Enzyme loading	25 (IU/g)	2.5
Enzyme prod.	400 (IU/l/h)	40.0
Enzyme yield	250 (IU/g/lactose)	25.0
Glucose yield	85 (%)	2.5
Feedstock cost	4.2 (Cents/kg)	0.4
Lignin credit	22.0 (cents/kg)	2.2

Figure 22 shows the results of the Monte Carlo simulation using the input values from Table 7. The base case run shows the expected value for ethanol price of about 48 cents per liter. When the lignin credit is added, the expected value drops to about 36 cents per liter. The expected value is found at the .5 (50%) probability point on the figure.

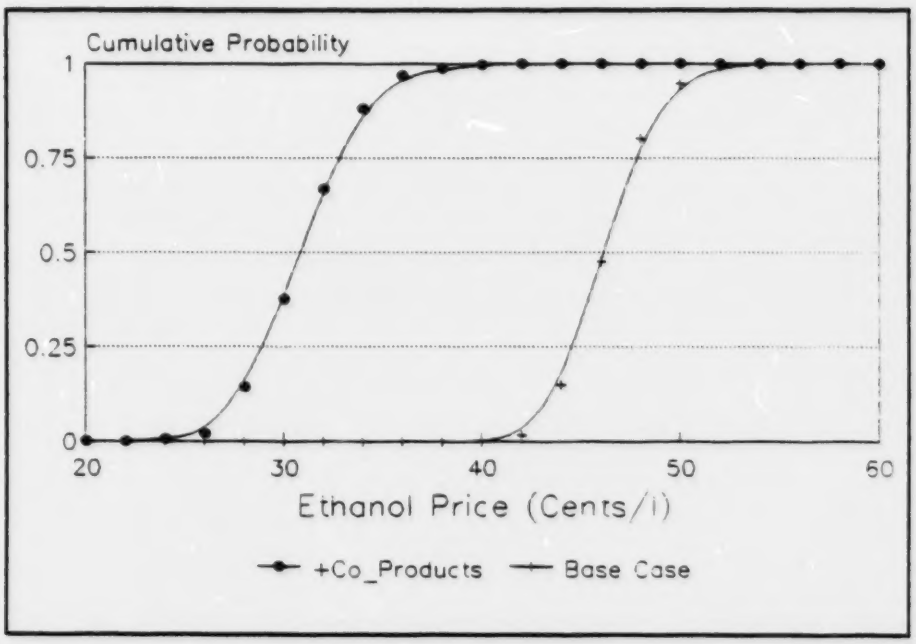

Figure 22. Monte Carlo Simulation: Iogen Base Case

The addition of the molasses as a co-product to this analysis only reduced the ethanol price another 2 to 3 cents per liter. This result occurred because it was necessary to import additional steam for the process that was formally provided for by burning the stillage. The same effect is observed with lignin, however the value of lignin is presumed higher than molasses and the net effect is that lignin is worth more as a co-product than as boiler fuel.

8.3 Improved Case Simulation

A Monte Carlo simulation was run to approximate an improved case for the Iogen process. Two simulations were run for the improved case: one without the lignin co-product credit and a second with the co-product credit. Table 8 shows the variables and the values used for this improved case simulation.

Table 8. Monte Carlo Simulation: Improved Case

Variable	Mean Value	Standard Deviation
Enzyme loading	12 (IU/g)	2.0
Enzyme prod.	1000 (IU/l/h)	125
Enzyme yield	400 (IU/g/lactose)	40
Feedstock cost	3.0 (cents/kg)	0.5
Hydrolysis time	40 (h)	4
Lactose cost	25 (cents/kg)	4
Lignin credit	30 (cents/kg)	5

These inputs were selected for their potential impact on the process economics and a reasonable expectation for attainability through research and engineering improvements to the process.

The rationale for using these particular input variables and values follows:

1. Enzyme loading can be reduced through improved pretreatment, a better enzyme preparation, or by using the SSF processing approach. Improvements in one or more of these areas should result in the reduction of the enzyme loading to 12 I.U. per gram of cellulose. The standard deviation of two suggests that a 95 percent chance exists that the value will fall between 8 and 16 I.U. per gram.

2. Enzyme productivity has increased dramatically over the past five or six years, going from 25 I.U. per liter per hour to in excess of 400 I.U. per liter per hour. Therefore it is reasonable to expect that the productivity will exceed 1000 I.U. per liter per hour in the next two years. (The values used for enzyme productivity in this simulation were 1000 I.U. per liter per hour for the mean and a standard deviation of 125.)

3. Enzyme yield is currently at 250 I.U. per gram of lactose. Improvements in process efficiency have the potential to double this value. The improved case uses a mean value of 400 I.U. per gram of lactose with a standard deviation of 40 to yield a 95 percent chance that the value will be between 320 and 480 I.U. per gram of lactose.

4. The feedstock cost in the base case is $42 per tonne or 4.2 cents per kg. Dedicated tree plantations are expected to produce wood for about $30 per tonne with improvements in yield, possibly obtained through genetic improvements, production costs could reach $20 per tonne. There is a high level of uncertainty in this number, therefore, the standard deviation is fairly broad at $5 per tonne and yields a 95 percent confidence that the wood would be priced between $20 and $40 per tonne.

5. Hydrolysis time can be reduced with improved processing techniques (e.g., the SSF approach reduces time via removal of end-product inhibition). In addition, improved substrate preparation and more active enzymes can also reduce the hydrolysis time. In the improved case, the mean hydrolysis time is set at 40 hours and the standard deviation is four hours.

6. Lactose cost has an input value of 23 cents per kilogram for the Iogen base case process design. However, there is a fair amount of uncertainty associated with this value caused by availability constraints on cheese whey. For the improved case, a mean value of 25 cents per kilogram was used along with a standard deviation of four cents per kilogram. This provided a range of values for lactose from 17 to 33 cents per kilogram.

7. The lignin co-product credit is used in the second improved case and is assigned a mean value of 30 cents per kilogram and a standard deviation of 5 cents per kilogram. This input suggest a 95 percent confidence that the lignin will sell for between 20 and 40 cents per kilogram. This higher value of lignin was used in the improved case based on the premise that in time higher valued markets for more highly refined lignin products would be identified and

developed. The wide standard deviation is consistent with uncertainty associated with finding high valued markets and the unknown cost for additional downstream processing.

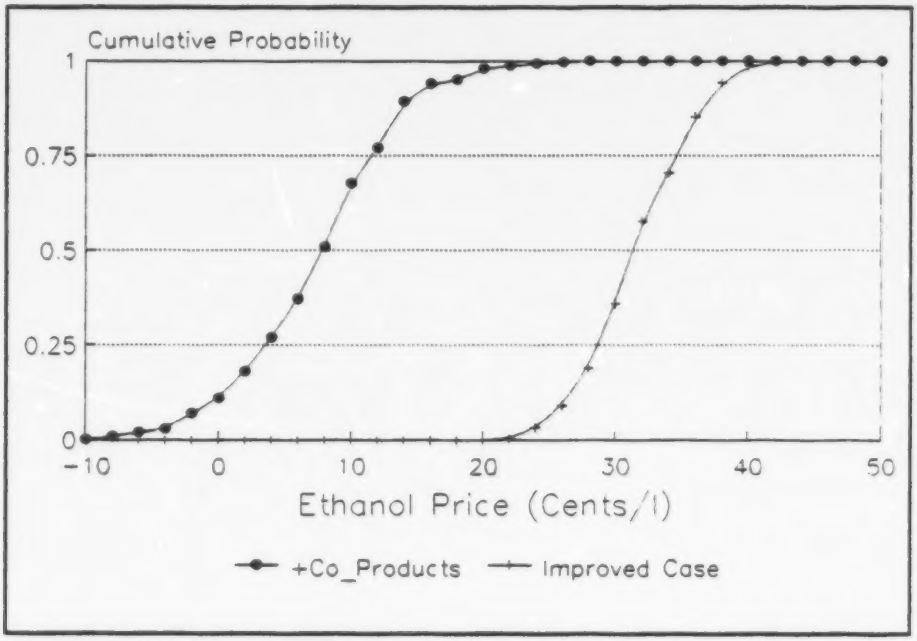

Figure 23. Monte Carlo Simulation: Improved Case

Figure 23 shows the result of the simulation which indicates that the achievement of the suggested improvements would yield an ethanol price of about 34 cents per liter without the co-product credits and about 12 cents per liter if the co-product lignin was added to the process. An additional reduction of 2 to 3 cents per liter would be obtained if the molasses co-product was also added.

8.4 Monte Carlo Simulation: Summary

The results of the three Monte Carlo simulations are combined and presented in Figure 24. The curve on the far right of this figure, labeled standard case, shows the technology from two to three years ago in which the conversion of wood to ethanol produced the product ethanol for about $1.20 per liter. The central curve represents the current Iogen base case and shows a required ethanol selling price of 48 cents per liter. It should be noted that this result

is obtained without the benefit of co-product credits. If co-product credits are added then the ethanol price drops to about 33 cents per liter.

This figure shows the dramatic improvement the Iogen process has made over conventional technology.

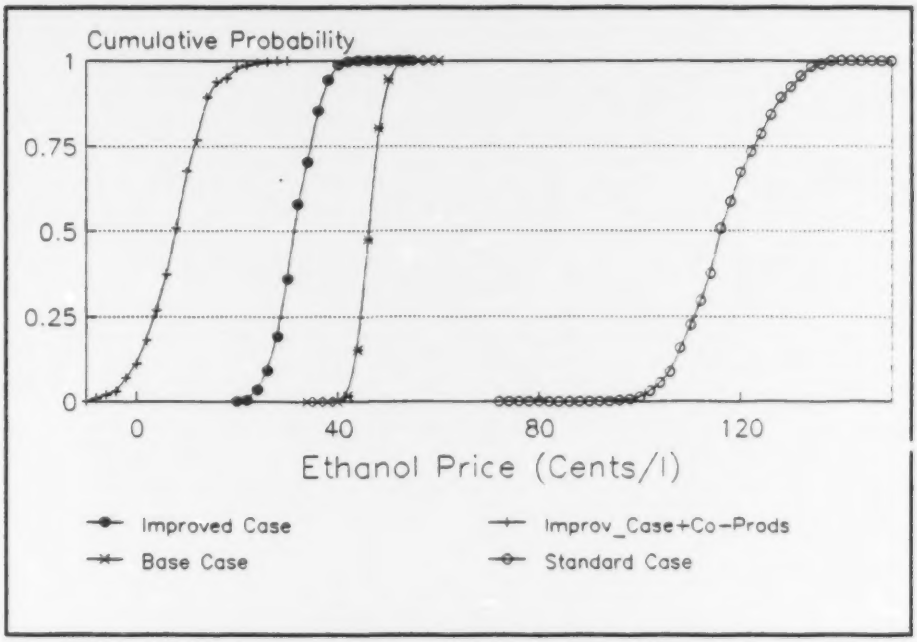

Figure 24. Combined Results of the Monte Carlo Simulations

The improved case shows an ethanol selling price of about 30 cents per liter without co-product credits. The research and technology improvements required to achieve this result should be attainable, with reasonable turn around on research goals, in two to three years.

The curve on the far left, with co-products included, is the improved process that assumes a mean value of 30 cents per kilogram for lignin credit and that ethanol from the C5 sugars is part of the commercial process. The result shown in this last curve will probably require an additional three to five years of research and engineering development to achieve. However, this scenario predicts an ethanol price of about 10 cents per liter would result from successful attainment of the target goals.

9 Second-law Analysis

The second-law analysis technique provides a thermodynamic basis for evaluating the energy efficiency of a process. The economic performance and energy efficiency should relate to the extent that low feedstock conversion yield or unutilized energy will produce more waste products and a higher cost end-product.

The second-law analysis generates an estimate of the energy efficiency of the individual operating units and the overall process efficiency. The measure that is used to assess the energy performance of the process is called lost work. Lost work is a combination of the first and second laws of thermodynamics that yields a more intuitive monitor of process efficiency than the usual second-law, or exergy, method. Lost work is the amount of work produced in a process subtracted from the potential work available from the process.

An ideal process, operated at equilibrium, would have zero lost work, however, it would take an infinite time to complete the reaction. In any real system, the process is operated away from equilibrium, i.e., energy is expended to cause the reaction to proceed at a reasonable rate. Some of this energy is lost, irretrievably, in the form of work and it is this lost work that contributes to the inefficiency of the process. The second-law analyses in Sections 9.1 through 9.4 show a comparison between a standard enzymatic hydrolysis process and various states of the Iogen process, from the base case through an improved case including co-products.

The second-law analysis is set up to measure the lost work for each of the operating units in the Iogen process.

- 200 is the pretreatment section and is constant through the analysis since we used a fixed input of wood and did not change the pretreatment conditions during the analysis.
- 300 is the enzyme production and hydrolysis systems measured together and the fermentation section. Fermentation contributes only a small amount of lost work to the process. It is the most energy-efficient process in the plant.
- 400 is the distillation section.
- 700 is the waste treatment section.
- 300 is the utilities section and consist of the heat

generation system, steam distribution system and the electrical generation systems.

It turns out that only five of the operating units make a significant contribution to the total lost work; namely, 200, 300, 400, 700, and 800.

In this analysis the lost work function is calculated for each of the operating units for the standard type technology. The difference between these values and the calculated values for the Iogen base case process are use to set up the stacked bar charts in Sections 9.2 through 9.4. In this way, one can compare the changes in total lost work for each modification of the process and for each operating unit against the standard process.

9.1 Standard Process

Figure 25 shows the lost work for the individual operating units and the total lost work for a standard wood-to-ethanol process using enzyme hydrolysis and growing the enzymes with cellulose as the carbon source. The processing conditions are those used in the standard process discussed in the Monte Carlo simulation in Section 8.1. The total lost work for this process configuration was 400,000 Btu per hour. The major contributors to this total are unit 300, hydrolysis and enzyme production, and unit 800, utilities.

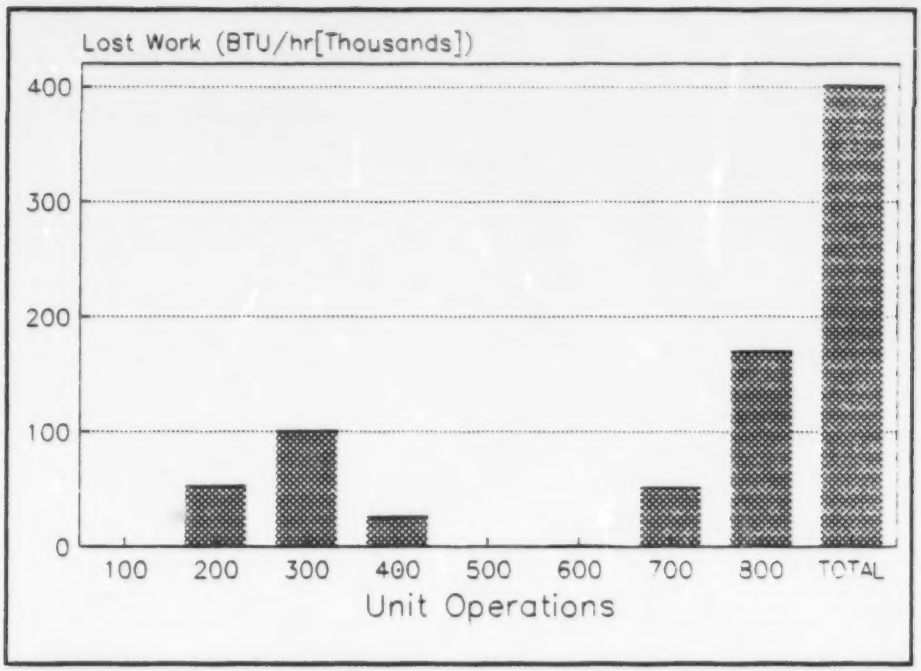

Figure 25. Second-law Analysis: Standard Technology

In this standard process the enzyme production section consumes energy in the form of electrical work to provide the mixing and aeration. The utility section produces a large amount of energy in the form of steam and electricity. There is a substantial amount of lost work, or lost potential to do work, in these operations that contribute to the inefficiency of the process. Modifications to the process that reduce lost work, in effect, illustrate ways to improve the process efficiency and economic performance.

9.2 Iogen: Base Case Process

The second-law analysis of the Iogen base case process produces a total lost work of 320,000 Btu per hour, or about 20 percent less than the standard process. Figure 26 shows the principal areas of energy and lost work reduction were operating units 300, 700 and 800. The largest reduction was in the hydrolysis and enzyme production sections (unit 300).

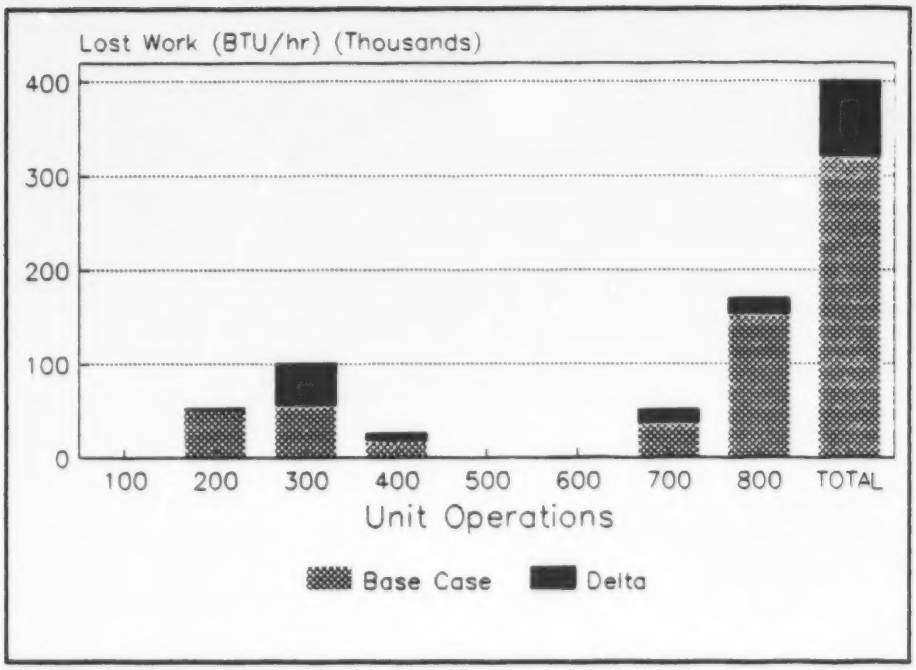

Figure 26. Second-law Analysis: Iogen Base Case

The hydrolysis yield was increased from 73 percent for the standard process to 85 percent for the Iogen base case design. The increased yield improved the efficiency of the process which shows up as reduced lost work in the hydrolysis section and a reduction in the required waste treatment energy. The increased enzyme productivity reduces the energy required for aeration and stirring the fermenters.

9.3 Iogen: Improved Case Process

The second-law analysis of the Iogen improved case is shown in Figure 27 and produced a lost work value of 270,000 Btu per hour, or about a 33 percent reduction from the standard process and a 15 percent reduction from the Iogen base case. The principal reductions occurred in operating units 300, 700 and 800 as was observed in the base case process; in addition a small contribution was observed from unit 400. The major contribution to reducing the lost work comes from the hydrolysis and enzyme production, section 300. The improved Iogen process has higher hydrolysis yield and enzyme productivity than the base case which accounts for the reductions in lost work.

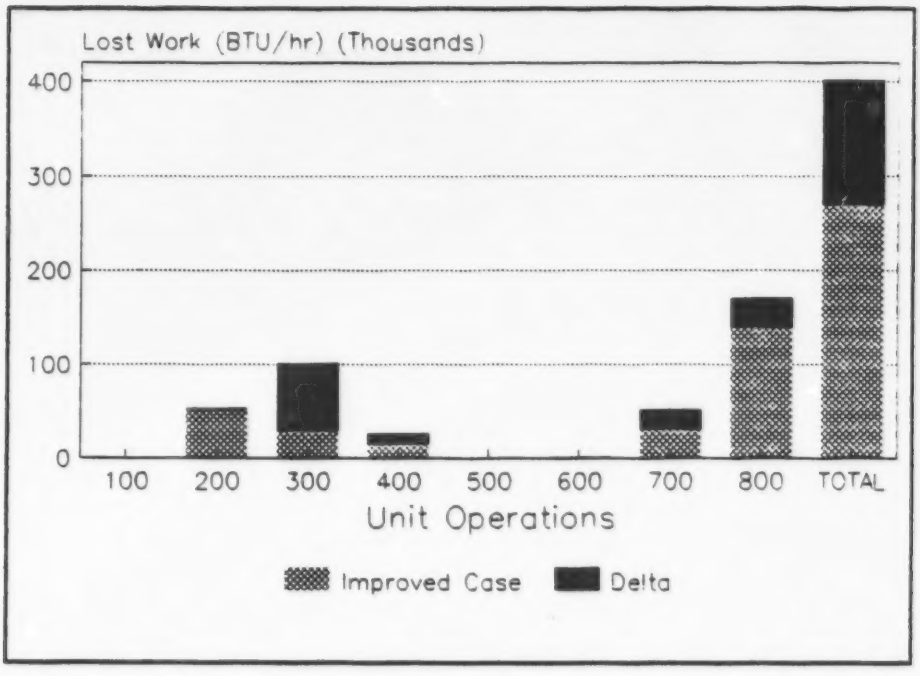

Figure 27. Second-law Analysis: Iogen Improved Case

The reduction in the distillation energy was caused by the process generating a higher glucose concentration during hydrolysis which produces a higher ethanol beer, thus requiring less energy for distillation.

9.4 Improved Case with Co-Products

The second-law analysis of the Iogen improved case with co-products added is shown in Figure 28 and produced a lost work value of 170,000 Btu per hour, or about a 58 percent reduction from the standard process and a 37 percent reduction from the Iogen base case. The principal reduction, compared to the Iogen improved case occurred in the utility (unit 800) operating unit. The utility requirements are reduced because the lignin and molasses are not dried when these streams are used as feedstocks to co-product processing. In this case, the molasses stream is converted to ethanol and adds about 40 percent more ethanol to the product stream and increases the efficiency of the process by converting more of the feedstock to useful, high-energy products.

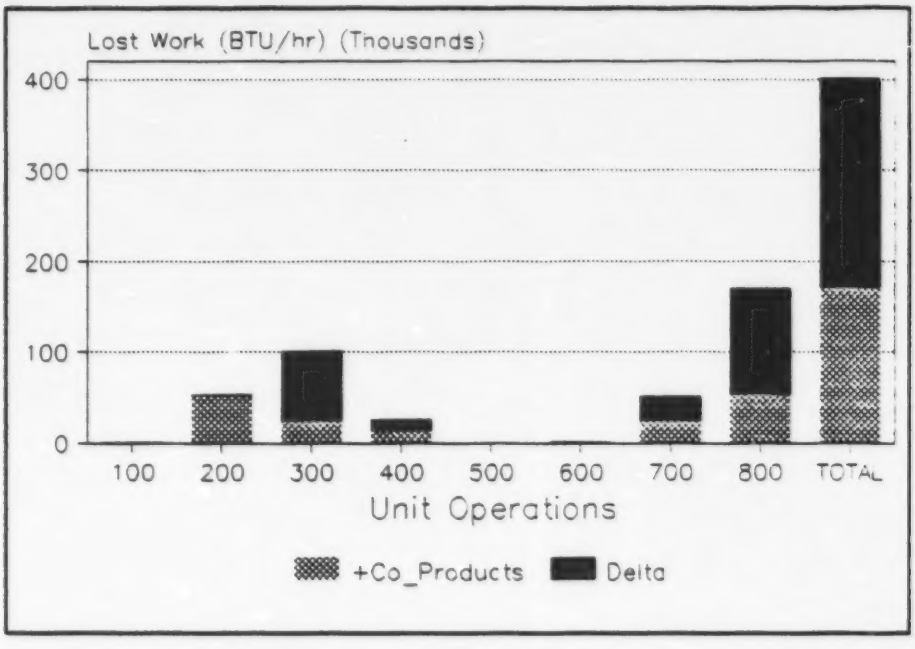

Figure 28. Second-law Analysis: Improved Case + Co-Products

9.5 Second-law analysis: Summary

The second-law analysis shows the Iogen process to be more efficient than the standard type process that uses cellulose to grow cellulase enzymes. The amount of lost work, i.e., the lost potential to do work, in the Iogen process is about 20 percent less than in the standard type technology.

The projected Iogen improved cases, with and without co-products, show additional significant reductions in lost work are possible. The analysis run using the input from the improved cases from the Monte Carlo simulations show reductions of 33 percent, and a 58 percent reduction from the standard process. Table 9 shows the comparison between the cases.

Table 9. Comparison of Total Lost Work

Process	Lost Work (MBtu/h)
Standard Process	401,000
Iogen: Base Case	320,000
Iogen: Improved Case	270,000
Improved Case + Co-products	170,000

The Iogen process is more energy-efficient than the standard wood-to-ethanol process that uses cellulose as the carbon source to grow the cellulase enzymes. The Iogen process has substantial room for increased efficiency based on the results of these second-law analyses. The Iogen base case process has a second-law efficiency of about 5 percent. The improved case with co-products has an efficiency of about 12 percent.

The standard efficiency range for mature industrial processes is between 15 and 25 percent. The nature of bioconversion processes is high energy efficiency and should produce systems that reach the upper end of this industry range, which suggests the Iogen process has additional room for energy efficiency and cost improvement.

10 Conclusions

The Iogen process is a state-of-the-art process for the enzymatic conversion of the cellulose fraction of woody feedstocks to ethanol, featuring co-production of chemicals and animal feed from the lignin and xylose fractions, respectively. The co-products add significant revenues to the plant, therefore enhancing the economic potential of the process. In fact, without the co-products, the process probably could not compete in a commercial environment.

The purpose of this section of the report is to review the strengths and weaknesses of the Iogen process and to estimate the potential for economic improvement through process refinements and/or technology improvements.

10.1 Enzyme Production

The enzyme production section of the Iogen process has the greatest economic impact. The use of lactose, a liquid substrate, as the carbon source for enzyme production simplifies the operation of the process and allows high productivity. The productivity is four to eight times higher than a comparable system using solid cellulose as the carbon source.

10.1.1 Lactose

Lactose proves to be a useful vehicle for technology development as the carbon source for cellulase enzyme growth because of the ability of lactose to induce a high level of activity in the enzyme complex. Cellulose also has this ability and is almost universally used for cellulase enzyme production.

The commercial adaptation of the Iogen process could be hampered by the lack of large quantities of lactose in any central location. In fact, the A.D. Little study (1985) of the Iogen process sited in upstate New York was scaled at a little over 20 million liters per year (five million gallons per year) because of the restrictions on available lactose. This same type of barrier exists in most of Canada and clearly could limit the commercial development of the Iogen process on a large scale if alternates to lactose are not explored and developed.

If lactose is a limiting resource, then what alternative carbon sources are available and what impact would substitutes for lactose

have on the process economics? This question can be answered based on today's technology and also based on expected research and engineering/process improvements in the near future.

At present, the only carbon sources that are available in sufficient quantity for commercial development are cellulose and the sugars from hydrolysis -- glucose and xylose.

10.1.2 Cellulose

The slow rate of cellulase enzyme production when cellulose is used as the carbon source is a consequence of the need to hydrolyze the solid substrate prior to fungal growth. That is, the fungus has to breakdown the cellulose to its component sugars before it can use the substrate for growth and cellulase production.

This barrier is substantial and there do not, at present, seem to be any viable methods to reduce the impact of this problem on the economic potential of the process. The consequence of this slow enzyme productivity is illustrated in Figure 5 and Figure 21, showing the sensitivity of ethanol price to enzyme productivity and the impact on the Monte Carlo simulation, respectively. Addition of credit for co-products will improve the economic performance in this case, but cannot produce a commercially competitive process without a very high price for the co-products.

The price of ethanol ranges between $1.40 and $1.00 per liter when the productivity is between 50 and 100 I.U. per liter per hour and no co-product credit is applied. The price is reduced by about 36 cents per liter if lignin is sold for 22 cents per kilogram.

10.1.3 Glucose and Xylose

Recent research has shown that glucose and xylose sugars can be used to grow cellulase enzymes. To date, however, research results indicate the activity of the enzyme complex produced is low. Research has also indicated that addition of a small amount of cellulose to the growth media, 2 percent to 5 percent, will induce the required activity and yield a balanced, active enzyme preparation. The productivity increases to the range of 150 I.U. per liter per hour when this procedure is used. The requirement of cellulose in the growth media as an inducer limits the rate of enzyme production.

If high activity can be induced without the cellulose, some researchers feel that cellulase growth rates approaching those achieved by lactose are attainable. Based on bench-scale data generated at Natick Laboratory (Allen and Andreotti, 1982), in which the researchers obtained higher cellulase yields from hydrolysis sugars than from lactose grown under similar conditions. These results suggest that future research could produce a system that uses wood sugars, glucose, xylose or other cellodextrines as the carbon source for enzyme production and achieve the high productivities than obtained with lactose. If this goal can be achieved, then the superior economic attributes of the Iogen process can be applied to a broad range of substrates and locations.

10.2 Co-Products

Co-products contribute a significant portion of the potential revenue streams to any wood-to-ethanol process. The value of these co-products are determined by a number of factors, including the product quality, the market size and the value in a competitive marketplace.

10.2.1 Lignin

The co-product price expected to obtain for lignin is a complex mixture of the factors mentioned earlier. In the base case, the lignin is used to furnish the energy for the process heating and electricity requirements and has a value of about 4.5 cents per kilogram.

Figure 29 shows the impact of lignin value in cents per kilogram versus the co-product credit associated with the value.

Table 10 shows typical markets for lignin and the value of lignin in those markets along with expected co-product credit and the approximate size of the market for each application.

Table 10. Lignin Markets, Market Size and Co-product Credits

Market	Lignin Value(cents/Kg)	Co-Product Credit(Cent/l)	Lignin Market(Kg*10^9)
Dispersants and surfactants	36.3	18.2	0.93
Asphalt extenders	16.5	7.7	2.05
Carbon black	47.1	24.5	0.48
Adhesives	7.4	14.6	0.34
Lignin plastics	25.0 - 31.6	30.7 - 46.5	0.67
Other polymeric applications	37.4	18.9	0.500
Average Lignin Value	29.8	Average Credits 15.5	Total Market 4.97

Source: SERI report #TR-231-2488 Chum et als. (1985).

Lignin could also be converted to gasoline fuel substitutes such as methyl aryl ethers. This would provide a very large market for the lignin with the market value for gasoline-type fuels about 20 cents per kilogram. This process has a high down stream processing cost and would limit the co-product credit to about 10 to 15 cents per liter. This options would provide an almost inexhaustible market outlet for the lignin co-product.

It is obvious from the values in Figure 29 and Table 10 that co-product credit from lignin has the potential to substantially impact the economic performance of the Iogen (or any other) wood-to-ethanol process. However, where the value of the lignin falls with respect to the potential markets is not as clear.

In the case of the lignin from the Iogen process, we must speculate about the impact of residual carbohydrates on the physical properties of the lignin and, therefore, the suitability for application in particular markets. How much downstream processing is required, and at what cost, to upgrade the Iogen lignin for use in high valued applications such as plastics and polymers? The answer to this question is outside of the scope of this analysis.

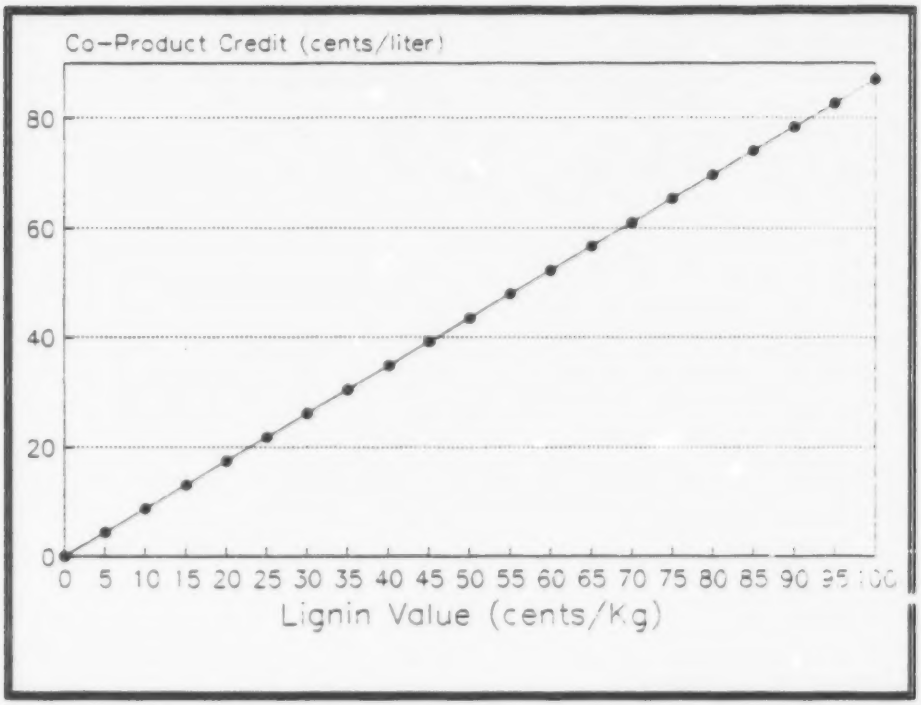

Figure 29. Lignin Co-Product Value versus Lignin Price

One 100-million-liter-per-year ethanol plant of this type would generate about 87 million kilograms of lignin per year. Of the higher value application in Table 10, one plant on this scale would output enough lignin to capture between 11 percent and 30 percent of the adhesives, plastics and polymer markets. Some of these markets could be saturated by as few as four commercial scale plants.

A number of questions remain regarding market penetration, transportation, location of the market in relation to the plant and price versus value of the lignin. The questions are outside of the scope of this report and are only mentioned to indicate the need for a careful market study before firm values can be assigned to lignin and molasses as co-products with ethanol in the Iogen process.

10.2.2 Molasses

The molasses produced in the Iogen process impacts process economics by about 2 to 3 cents per liter if the lignin has already been removed. The reason for this small impact is the necessity to

import additional steam for the process if both lignin and molasses are removed. The lignin has a higher potential co-product value and would normally be removed from the process prior to molasses. However, if the lignin is left in the process to provide heat and electricity, then the molasses contributes about 11 cents per liter credit to the economic output of the process, assuming a credit of $121 per tonne as animal feed.

10.2.3 Electricity

Electricity is generated as a by-product of the process and is a revenue generator only when electricity in excess of the plant requirements is produced. The model uses 2.92 cents per kilowatt hour as the electricity credit value. This value is the cost of generation and is the minimum value used in the model.

10.3 Alternate Processing Schemes

There are a few alternate processing approaches that may benefit the Iogen plant design. Three of these are discussed below and offered as process changes with a potential for significant economic benefit. One is lignin extraction before the hydrolysis step; a second is using the SSF scheme in preference to the SHF approach used in the Iogen process design; and the third is the addition of xylose fermentation to ethanol.

10.3.1 Lignin Extraction

Extracting the lignin prior to hydrolysis has a couple of beneficial effects on the process and subsequent economics. Lignin is generally extracted with alcohol or a basic aqueous solution. In either case the lignin is of higher quality than the Iogen type fermentation lignin, meaning free of major contaminants such as unhydrolyzed carbohydrates. The extraction also acts as a first step in downstream processing of the lignin.

The removal of lignin serves to reduce the required size and capital cost of some downstream equipment, particularly, the hydrolysis section of the plant. Most research data supports the fact that removing lignin reduces the amount of cellulase enzyme needed to effect hydrolysis of the cellulose to glucose.

10.3.2 SSF versus SHF

The SSF process has several beneficial attributes that appear to offer an economic alternative to the SHF approach. End-product inhibition causes the hydrolysis process to slow down after the accumulation of sugars in the hydrolysis reactor. The principal methods to overcome this problem are to add supplemental enzymes, to increase the hydrolysis time or to accept a lower hydrolysis yield. All of these are costly options and among the principal bottlenecks of the economic refinement of the SHF process.

The SSF approach attacks all three of these problems and not only ameliorates each, but causes a reversal of the problem and enhances the performance in these areas. The SSF process reduces the enzyme loading requirement to about 10 I.U per gram of cellulose. Under similar conditions, a SHF process would require in excess of 25-40 I.U. per gram cellulose.

The SSF process works via a push-pull mechanism, that is, by using the glucose sugar as fast as it is generated, the end-product inhibition is substantially reduced or eliminated, and the hydrolysis proceeds at a faster rate. Higher ethanol concentrations are reached sooner, with a side benefit of reduced problems associated with asepsis. However, in this processing scheme the optimum temperature is different for hydrolysis and fermentation. Hydrolysis has an optimum temperature of 50°C, while the fermentation has its optimum at 37°C. Numerous schemes have been tried to circumvent this mismatch, including isolating thermophilic yeast. However, the benefits of the process are great enough to allow running the entire process at 37°C while still obtaining a substantial improvement over the SHF process.

Reducing the enzyme loading to 10 I.U. per gram of cellulose from the base case value of 25 I.U. per gram would reduce the ethanol price to about 40 cents per liter and the actual cost reduction would be more, since the capital cost is also reduced.

Based on these simple changes the SSF process seems to have a substantial advantage over SHF.

10.3.3 Xylose to Ethanol

Conversion of the xylose sugars to ethanol is another technology area that substantially improves the economic posture of the Iogen process. Converting xylose to ethanol reduces the base case ethanol price by 15.25 cents per liter from 48.04 cents per liter to 32.79

cents per liter. At present, the process to effect this conversion is a research issue. The conversion is slow and requires a different microorganism to ferment the sugars and a set of operating parameters different from those used to ferment glucose.

Significant progress has been made in this area over the past two years, and it is not unreasonable to expect a compatible system to be developed in the next two or three years, given the level of ongoing research.

10.4 Potential Process Improvements

The Iogen process is a highly optimized enzymatic hydrolysis process for the conversion of cellulosic feedstocks to ethanol and co-products lignin and molasses.

Question: Is this the best performance to be expected from the process? If not, where should we look for future refinements?

Table 11, in section 10.4, shows the economic impact of process improvements in five key areas. The net effect if all five goals are accomplished will be to reduce the require ethanol selling price by 18.89 cents per liter to 29.15 cents per liter from the base case ethanol price of 48.04 cents per liter, without co-product credits. If co-product credits are added for lignin at 22 cents per kilogram and molasses at 12.1 cents per kilogram the require ethanol selling price is reduced to 11.10 cents per liter. If the C5 sugars are converted to ethanol instead of molasses the required selling price for ethanol is 14.25 cents per liter.

These results point out the areas of technological improvement that produce the greatest change to the economics posture of the Iogen process. Each of these process targets is achievable with an additional 2 to 3 years of research and engineering development.

Table 11. Potential Process Improvements

Process Step	Base Case	Improvement	Delta Ethanol Price
Enzyme productivity	400	1600	-5.61
Enzyme loading	25	10	-8.27
Glucose yield	85%	100%	-7.47
Solids loading	15%	20%	-2.83
Enzyme yield	250	400	-2.39

	Ethanol Price cents/liter
The net impact of summing these changes would result in an ethanol price of:	29.15
With co-product lignin at 22 cents per kg and molasses at 12.1 cents per kg, the ethanol price	18.14 11.10
With xylose fermentation the ethanol price is and with lignin co-product credit at 22 cents per kg	21.00 14.25

The ultimate potential of the Iogen process will be determined by the co-product value obtained for the lignin and molasses, and with further improvement in fermentation of xylose sugar to ethanol. The economic impact of this additional alcohol, from xylose, could reduce the required ethanol selling price by 15.25 cents per liter from 48.04 to 32.79 cents per liter for the Iogen base case; in the improved case described in Table 11 this additional ethanol will drive the ethanol price down to about 21 cents per liter. With the lignin credit at 22 cents per kg, the price would be about 14.25 cents per liter.

This is not as low as the improved case with xylose being sold as molasses, where the required ethanol selling price with lignin and molasses is 11.10 cents per liter. The principal reason for this effect is that the additional ethanol increases the amount of product by 40 percent and thus reduces the impact of co-product lignin. Also the additional capital costs associated with fermenting the xylose increases the net selling price of ethanol. As more research

and engineering is completed on xylose fermentation to ethanol we can expect capital costs to be reduced and the ethanol price to be reduce by another 3 to 5 cents per liter.

If tree farming and genetic modification of tree stock succeeds in producing a feedstock that sells for $20 per tonne, then an additional reduction of 5 to 7 cents per liter in the required ethanol selling price would be obtained for these improved cases.

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